Carderock Division
Naval Surface Warfare Center
Bethesda, MD 20084–5000

CARDIVNSWC–TR–61—94/15 July 1995
Survivability, Structures, and Materials Directorate
Technical Report

Evaluation of Galvanic and Stray Current Corrosion in 70/30 Copper-Nickel/Alloy 625 Piping Systems

by
Harvey P. Hack and Walter L. Wheatfall

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ABSTRACT

Because of the difficulty in ensuring full-time electrical isolation of dissimilar metal piping, alternate methods of coping with galvanic corrosion must be used. Use of short, electrically isolated piping sections between dissimilar metals can reduce galvanic corrosion by increasing the electrical resistance of the seawater path through which the galvanic current must flow. The objective of this project was to determine the magnitude and distribution of galvanic corrosion of 70/30 copper-nickel piping when coupled to alloy 625 piping, to determine the efficacy of various lengths of isolated separator pipes made of either alloy, and to determine the amount of stray current corrosion that could occur on the separator piping as a function of pipe material.

The presence of separators of any length in 2-in. pipe lowered the amount of galvanic corrosion between copper-nickel and alloy 625, with a 50- to 60-percent reduction in metal loss using 3-ft (1-m) separators. A further reduction of another 30 to 50 percent was achieved by increasing the separator length to 10 ft (3 m). The use of copper-nickel separators generally resulted in higher metal losses than the use of alloy 625 separators. The effect of the separator was maximum under low flow conditions. Alloy 625 separators were more effective than copper-nickel separators. Smaller diameter copper-nickel pipe experienced higher corrosion rates than pipe of equal diameter to the alloy 625 pipe to which they were coupled. Linearity of potential profile through the separators was an accurate indicator of whether stray current corrosion was taking place.

The Navy should use 3-ft (1-m) titanium separator pipes, electrically isolated at both ends, to minimize galvanic corrosion in 2-in.-diameter dissimilar metal seawater piping joints.

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ADMINISTRATIVE INFORMATION

The Naval Sea Systems Command (Code PMS 350T14 [Michael Peterson]) sponsored this project. Work was conducted under work unit 1–2813–801 in the Marine Corrosion Branch (Code 613) under the direction of Mr. Robert Ferrara. Mr. David Greenlaw and the staff of the LaQue Center for Corrosion Technology—under the direction of Mr. Robert Kain and Mr. Dennis Melton—conducted outfitting and testing of the

piping mockups. Mr. Greenlaw also performed mockup tear-downs and aided with visual inspections.

ABBREVIATIONS

DTRC	David Taylor Research Center (former name of the Carderock Division, Naval Surface Warfare Center)
PVC	Polyvinyl chloride
RISIC	Rubber insert sound isolation coupling
UNS	Unified numbering system
ZRA	Zero-resistance ammeter

INTRODUCTION

POTENTIAL CORROSION PROBLEMS

To improve operational performance, the Navy is considering replacing some of the 70/30 copper-nickel (UNS C71500) in seawater piping systems with alloy 625 (UNS N06625), creating a possibility for galvanic corrosion problems where the dissimilar metal piping materials are joined. Electrical isolation at the interface is an obvious choice as a preventative measure. For this reason, bimetallic rubber insert sound isolation couplings (RISICs) and nonconductive flexible hoses were incorporated into the original designs of new seawater piping systems in ships that use both piping materials together. Unfortunately, detailed design analysis discovered that RISICs and hoses cannot effectively electrically isolate the dissimilar metals because of the significant number of alternate paths for electrical shorting of the dissimilar metals. Such paths include pipe hangers, electrical safety grounding straps, electrically actuated pump and valve electrical grounds, and metal-braided hydraulic lines. Unintentional, intermittent grounding is also possible through the inadvertent placement of metal ladders, tools, and steel wool pads used for cleaning.

Because of the difficulty in ensuring full time electrical isolation of the dissimilar metal piping components, alternate methods of coping with the galvanic corrosion must be used. One method is the use of replaceable sections of heavy-walled copper-nickel piping near the transition point—called inspection or waster pieces. The length, wall thickness, and replacement periodicity of such replaceable piping sections must be determined based on the maximum localized galvanic corrosion rate of the copper-nickel and on the distribution of the corrosion as a function of the distance from the interface. The extent of the corrosion will depend on the effective area ratio of the dissimilar materials, which is, in turn, dependent on the distribution of the galvanic current along the inside of both piping materials. The distribution of the corrosion is based on the distribution of the galvanic current along the inside of the copper-nickel piping. Unfortunately, these current distributions are not presently known.

Electrically isolating large pipe sections is not always practical because alternate electrical paths can exist through pipe hangers, electrically actuated valves, etc. Use of a short piping section between dissimilar metals, which is electrically isolated from the pipe on either side, can reduce galvanic corrosion by increasing the electrical resistance of the seawater path through which the galvanic current must flow. This occurs even when an alternate electrical path exists that electrically connects the dissimilar metal piping on either side of the isolated short section. Short piping sections—without valves, pumps, or pipe hangers—can be more readily electrically isolated while eliminating the alternate electrical paths that would exist in more complex systems. The degree of galvanic corrosion mitigation is dependent on the length of the isolated piping sections in a way that is currently unknown. In addition, such piping sections could suffer from stray current corrosion effects because they will be placed in an electrical field gradient caused by the galvanic current. The magnitude of the stray current corrosion of the isolated sections is dependent on their material and the extent of galvanic corrosion. This, also, is currently unknown.

PROJECT OBJECTIVE

The objective of this project was to determine the magnitude and distribution of galvanic corrosion of 70/30 copper-nickel piping when coupled to alloy 625 piping, to determine the efficacy of various lengths of isolated separator pipes made of either alloy, and to determine the amount of stray current corrosion that could occur on the separator piping as a function of pipe material. This research was also intended to determine whether a bimetallic crevice at a flange creates a worse crevice corrosion circumstance than a similar crevice of only one material at the same electrochemical potential.

Because piping systems typically either carry seawater at the nominal design velocity or are shut down and carry seawater with no flow, information was obtained under both flowing and near-stationary flow conditions. Testing was designed to simulate certain areas of piping systems under both low flow and flowing conditions.

APPROACH

A series of piping mockups was designed to simulate the most probable geometry and environmental conditions existing, on average, in the piping systems of interest. This information was based on pipe system drawings and knowledge from cognizant Naval Sea Systems Command personnel. Nineteen piping mockups were designed with various material combinations, geometries, flows, and separator pipe lengths (see Figure 1). These mockups were constructed and operated at the LaQue Center for Corrosion Technology, Wrightsville Beach, NC.

MATERIALS AND CONSTRUCTION

Twenty-two 10-ft (3.3-m)[a] sections of nominal 2-in. pipes were procured of each material. Alloy 625 welded tubing was procured to ASTM B 705–82,[b] class 2. 70/30 copper-nickel, type 1 seamless tubing was procured to MIL–T–16420K,[c] grade 1, except that the wall thickness and inside diameter were required to be that of the nominal 2-in.-diameter pipe. All nominal 2-in. pipe was schedule 40, 2.375 in. (6.03 cm) od by 2.067 in. (5.25 cm) id by 0.154 in. (0.39 cm) wall thickness. One pipe each of nominal 1-in. and 1.5-in. 70/30 copper-nickel for mockups 18 and 19 was procured to the full requirements of MIL–T–16420K, including wall thickness and inside diameter. The 1-in. pipe was class 700, and the 1.5-in. material was class 1650. Mechanical properties and chemical compositions of all of the piping alloys are shown in Table 1.

The five nominal 2-in. flanges of each material to be used in mockups 1 through 5 were procured as forgings rated at 700 lbf/in^2 (4.8 MPa) to Navy Bureau of Ships drawing no. 810–1385861. Table 1 contains mechanical properties and chemical compositions of all of the flange materials tested.

Titanium/copper-nickel bimetallic RISICs for mockups 3 through 5 were procured from both Aeroquip[d] and Murdock.[e] The RISICs are similar in design, in materials of

[a]The English system of measuring was used in this work.

[b]"Standard Specification for Nickel-Alloy (UNS N06625 and N08825) Welded Pipe."

[c]"Tube, Copper-Nickel Alloy, Seamless and Welded (Copper Alloy Numbers 715 and 706)" (14 Apr 1978).

[d]1225 W. Main St., Van Wert, OH.

[e]Box 152278, Irving, TX.

construction, and in principles of operation. A schematic drawing of the Murdock type 1 RISIC–2A is included as Figure 2. The body end is 70/30 copper-nickel (grooved), and the attached flange (grooved) is made from titanium. In the test setup, the 70/30 copper-nickel end was bolted to the 70/30 copper-nickel flange, which was welded to the 70/30 copper nickel pipe; the titanium end was attached to the alloy 625 flange, which was welded to the alloy 625 pipe.

Polyvinyl chloride (PVC) compression sealing fittings were used to connect the unflanged joints of the various sections of pipe to each other, to the manifolds, to the rotameter, and to the other system components. Figures 3 to 5 show some of the different views of the mockup assemblies. The main seawater supply line to the mockup assembly was nominal 6-in. PVC pipe. Service to individual mockups was achieved by tapping this 6-in. manifold with nominal 4-in. tee connectors (see Figure 3). Nominal 2-in. PVC globe valves were used, along with nominal 4-in.-by-2-in. reducers, to regulate the flow of seawater to each mockup. A rotameter was inserted in the discharge end of each mockup (see Figure 4). Figure 5 shows an overall view of the mockups under construction.

EXPERIMENTAL PROCEDURE

The mockups were operated for 1 yr, with shutdown and disassembly after 6 mo to examine the progress of the corrosion. Each mockup was shut down individually and disassembled for measurement with a minimum of disturbance to the corrosion products that had already formed or to the operation of the other mockups. The exact flow maintained in each mockup is shown in Figure 1.

GALVANIC CURRENT MEASUREMENTS

Galvanic current measurements were made between the outer copper-nickel and the alloy 625 pipe sections on all mockups except 1 and 2, where these sections were flanged and bolted together, creating an electrical short circuit. A zero-resistance ammeter (ZRA) was used to make the readings. Current measurements were made daily for the first week of exposure and then on a weekly basis for the remainder of the 1-yr exposure. The ZRA was connected only when the readings were actually being taken. At other times, the outer pipe sections were maintained in electrical contact by external wiring. To avoid interruption of current flow while connecting the ZRA, the ZRA was first hooked up parallel to the regular system wiring. Then, the normal wiring was disconnected while the current flow was measured with the ZRA. The regular wiring was reconnected before the ZRA wiring was disconnected at the conclusion of the measurement. The middle separator section of mockups 6 through 17 were not electrically connected to either outer pipe section; thus, no current readings were possible.

POTENTIAL MEASUREMENTS

Corrosion potential vs. distance measurements were made several times during the 1-yr exposure period on all mockups. These measurements were made in 1-ft (30-cm) increments from the seawater inlet side to the discharge end of the pipes. Mockups 14 through 17 exceeded 30 ft (9 m) in length. Therefore, an Ag–AgCl reference electrode was mounted in a very long probe. Figure 6 is a schematic drawing of the potential measuring probe. In the design of the probe, the following major objectives were pursued:

1. To allow potential measurements to be made in each mockup while seawater was flowing under normal test conditions;
2. To have no interruptions in the other mockups while measurements were being made in one;
3. To maintain the reference electrode in the center of each pipe during the course of the measurement;
4. To seal the electrical lead wire against contact with the seawater.

The scraping force of the probe against the pipe walls was also designed to be at a minimum. These goals were achieved through the use of PVC in the construction of the probe and the pipelines.

The "upstream" end of each tee connection on the seawater inlet end of each mock-up had a screw-on plug, which was used during normal operation of the system. When potentials were taken, the incoming water was shut off with the PVC globe valve, and the plug was unscrewed and replaced with the reference electrode probe. The seawater flow was then restarted and adjusted. After the system stabilized, the potentials were measured. Initially, one set of readings was taken traversing the length of the pipe from the seawater inlet end (inserting the probe). Later, a set of readings was also taken while withdrawing the probe from the pipe. The second set was taken because of the possibility that the probe guide fins might damage the corrosion products on the inner walls of the pipe. A significant difference between the "in" and "out" potentials would have indicated this occurrence. The flexible plastic tubing that covered the reference cell lead wire and acted as a push rod for the reference cell assembly was later changed to rigid plastic tubing after it was discovered that the flexible tubing was kinking and not stretching to its fullest extent inside the test pipes. Thus, the potential readings taken just before this probe reconstruction had inaccuracies in longitudinal positioning.

PHYSICAL MEASUREMENTS

At the 6-mo inspection and at the conclusion of the 1-yr exposure the pipes were visually examined and observations were made on corrosion product films, fouling, corrosion depth and distribution on pipe interiors, and corrosion depth on pipe exteriors. Whenever appropriate, measurements were made of corrosion depth on pipe exteriors using a pointed depth gauge. At the conclusion of the 1-yr exposure, the pipes were lightly cleaned with a stiff brush to remove large fouling organisms, rinsed, and returned to the Carderock Division, Naval Surface Warfare Center for evaluation. Corrosion of the interior surfaces was measured by cutting off 18-in. (46-cm) sections at the ends of the pipes and splitting them in half lengthwise. The depth of any deep pits and their distance from the pipe end was then determined using a pointed depth gauge, a micrometer, and a ruler. No measurements were taken on the alloy 625 pipe sections because the interior never experienced any measurable corrosion.

RESULTS AND DISCUSSION

GALVANIC CURRENTS

The galvanic currents that were measured between the alloy 625 and the copper-nickel coupled pipes (shown in Table 2) started high and decayed with time, but were too

erratic to easily determine a steady-state current. Instead, each current time curve was integrated to determine the total charge passed during the exposure. The result should have been closely related to the total amount of metal loss of the coupled copper-nickel section. These integrated current values, determined for each piping mockup after 6 mo and, again, after the 1-yr exposure, are plotted in Figures 7 to 12.

Figures 7 and 8 show after 6-mo and 1-yr exposures, respectively, the integrated current values for all mockups with 2-in. copper-nickel pipe and a flow of 6.0 ft/s (1.8 m/s). Data mockups with 1-, 3-, and 10-ft (0.3-, 1-, and 3-m) separators of both materials are presented. Data for the mockups with Aeroquip and Murdock RISICs are plotted at zero on the graph, and their average is shown vertically—halfway between. The presence of separators of any length lowered the amount of metal loss, with a 50- to 60-percent reduction using 3-ft (1-m) separators. A further reduction of another 30 to 50 percent was achieved by increasing separator length to 10 ft (3 m). The use of copper-nickel separators resulted in higher metal losses than the use of the alloy 625 separators in all cases except 1 ft (0.3 m), probably because of a spuriously high integral for the 1-ft (0.3-m) alloy 625 separator mockup. Galvanic current can flow by two parallel paths past the separators: through water or through the separator (stray current). The resistance of copper-nickel to stray current corrosion is lower than that for alloy 625. The current integrals are probably higher for the mockups with copper-nickel separators because of the lower electrical resistance of the stray current corrosion path for this material.

Figures 9 and 10 show similar data for the mockups with less than 1 ft/s (0.3 m/s) flow. Overall currents for mockups with separators under low flow are higher than under flowing conditions by a factor of up to two. It appears that separators are more effective at controlling galvanic corrosion under low flow conditions than at 6 ft/s (2 m/s). Most of the metal loss suppression occurred with 3-ft (1-m) separators. The use of longer separators had little additional effect. Significantly greater suppression of metal loss occurred using the alloy 625 separators, as previously observed for higher flow conditions.

Figures 11 and 12 show the effect of changing the diameter of the copper-nickel pipe on the current integral. As in Figures 7 and 8, the points at the 2-in. diameter represent the Aeroquip and Murdock RISICs, with the average value of these RISICs plotted vertically halfway between the individual values. The plotted curve is nearly horizontal, indicating little effect of diameter on total metal loss. Because the same total metal loss must be absorbed by smaller diameter pipe as by larger diameter pipe, the loss per unit area must be greater on the smaller pipes. This is the area ratio effect and is expected under conditions where the total corrosion is controlled by the cathodic (alloy 625) surface.

In summary, separators can significantly reduce galvanic corrosion of 2-in. copper-nickel pipe coupled to the alloy 625 pipe—with 3 to 10 ft (1 to 3 m) being optimum. The effect of the separator is maximum under low flow conditions. The alloy 625 separators are more effective than copper-nickel separators. Smaller diameter copper-nickel pipe will experience higher corrosion rates than pipe of equal diameter to the alloy 625 pipe to which they are coupled.

POTENTIALS

Potential readings taken during the course of the exposure are shown in Table 3. Figure 13 is a plot of potential profiles on the inside of the mockups without separators after about 6 mo exposure. The first 10 ft (3 m) are within the alloy 625; the next 10 ft

(3 m) are within the copper-nickel. The potential of the copper-nickel was relatively unaffected by distance from the interface beyond the first foot (0.3 m). Potential changes in the copper-nickel because of changes in pipe diameter could not be measured because the pipes with diameters smaller than 1 in. were too small for the probe. Surprisingly, the potential and profiles inside the alloy 625 were also relatively unaffected by changes in the copper-nickel pipe diameter until the smallest diameter was reached. Predictably, the alloy 625 should polarize less when connected to the lesser area of copper-nickel of the 1-in. pipe; however, the opposite occurred. The potential behavior of this pipe is, therefore, unexplainable.

Figure 14 shows potential readings for all mockups with and without separators tested at 6 ft/s (2 m/s) flow with nominal 2-in. copper-nickel pipe. As in Figure 13, the first 10 ft (3 m) are within the alloy 625. The last 10 ft (3 m) of each curve are within the copper-nickel. Depending on the length of the separator, a length from zero to 10 ft (3 m) between these indicates potentials within the isolated separator piece. A fully isolated pipe in this area, where no current is lost to the walls of the separator, should theoretically yield a straight line on this type of plot, with a slope proportional to the seawater path resistance. This linearity is seen in Figure 14 for the 10-ft (3-m) alloy 625 separator (indicated as ▽), where the separator piece is located between the 10- and 20-ft (3- and 7-m) positions. The curve is also linear for the 3-ft (1-m) alloy 625 separator (indicated as △), where the separator piece is located between 10 and 13 ft (3 and 4 m). The 10-ft (3-m) and 3-ft (1-m) copper-nickel separators (indicated as × and ◇) both show significant nonlinearity of potential inside of the separator. This can only occur if current is entering or leaving the walls of the separator indicating that stray current corrosion may be occurring on these separators. In fact, stray current corrosion was observed on the copper-nickel separators but not on the alloy 625 separators. Linearity cannot be determined for the 1-ft (0.3-m) separators of either material because potential readings were taken only every foot (0.3 m).

Figure 15 shows potential readings for all mockups with and without separators tested at less than a 1-ft/s (0.3-m/s) flow. As in Figure 14, the first 10 ft (3 m) are within the alloy 625; the last 10 ft (3 m) are within the copper-nickel. A length from zero to 10 ft (3 m) between these is within the isolated separator piece. Also, as stated previously, linearity of potential is not possible to observe for the 1-ft (0.3-m) separators. The 3- and 10-ft (1- and 3-m) copper-nickel separators show nonlinearity, indicating a possibility of stray current corrosion, and the 3-ft (1-m) alloy 625 separator shows linear potentials. Unlike Figure 14, the 10-ft (3-m) alloy 625 separator shows nonlinear potentials. In fact, this is the only instance where corrosion was actually observed on the alloy 625 after 6 mo exposure. Corrosion was due to stray current accelerated crevice corrosion on the exterior of the pipe under the compression fitting gasket.

Figures 16, 17, and 18 are the same plots as Figures 13, 14, and 15, except they indicate an exposure time of 1 yr. Figure 16 is a plot of potential profiles on the inside of the mockups without separators after about 1 yr of exposure. There is more data scatter than the 6-mo data in Figure 13. The potential of the copper-nickel was relatively unaffected by distance from the interface beyond the first 2 ft (0.7 m), indicating a spreading of the corrosion effects. Potential changes in the copper-nickel because of changes in pipe diameter still could not be measured. The potential and profiles inside the alloy 625 were highly variable, making it impossible to assess the effects of changes in copper-nickel

pipe diameter. The potential behavior of the alloy 625 connected to the 1-in.-diameter copper-nickel pipe were still quite different from the behavior of the other pipes and, thus, still unexplainable.

Figure 17 shows potential readings for all mockups with and without separators tested at a 6-ft/s (2-m/s) flow with nominal 2-in. copper-nickel pipe after about an exposure of 1 yr. Linearity of potential within the separator areas is not seen, even for the alloy 625 separator where it was obvious after 6 mo exposure. This indicates that stray current corrosion may be occurring on all separators of both materials. In fact, stray current corrosion was actually observed on the copper-nickel separators and on the longer alloy 625 separators (in the form of stray current-induced crevice corrosion on the outside of the pipe end under the tubing used to hold the sections together). Linearity still could not be determined for the 1-ft (0.3-m) separators of either material.

Figure 18 shows potential readings for all mockups with and without separators tested at less than a 1-ft/s (0.3-m/s) flow after about 1 yr of exposure. The 3- and 10-ft (1- and 3-m) copper-nickel separators show nonlinearity, indicating a possibility of stray current corrosion, and the 3- and 10-ft (1- and 3-m) alloy 625 separators show linear potentials. Stray current corrosion was actually observed on the copper-nickel separators, whereas no corrosion was actually observed on the alloy 625 separators at less than 1 ft/s (0.3 m/s) flow after 1 yr of exposure.

In summary, linearity of potential profile through the separators was an accurate indicator of whether stray current corrosion was taking place. Copper-nickel separators always indicated current loss through the walls of the separators, whereas the alloy 625 indicated current loss only in those few cases where stray current-induced crevice corrosion was observed on the separator piece. The longer separators seemed to have a greater tendency for nonlinear behavior, which is consistent with the theoretically higher driving force for stray current corrosion when the alternate seawater path resistance is higher.

VISUAL OBSERVATIONS AND PHYSICAL MEASUREMENTS

6 Months Exposure

Visual observations of the pipe and RISIC sections after 6 mo exposure are presented in Appendix A and summarized next. In many cases it was difficult to assess the depth or the extent of the corrosion because of obscuring effects of corrosion product films or fouling and slime layers. This material was not removed, thereby providing minimal disturbance to the corrosion process. These pipes were to be reexposed after analysis.

All sections of the alloy 625 pipe and all titanium areas of the RISIC showed no visible corrosion after exposure, with one exception. This was true whether the flow was low or moderate and for both inlet and outlet ends and was expected because these alloys are both naturally corrosion resistant and cathodically protected by the copper-nickel. The one exception to this was an area of extensive crevice corrosion on the alloy 625 under a rubber sealing ring on the isolated 10-ft (3-m) separator section in the low flow mockup (see Figure 19). This corrosion was 65 to 75 mils (1.9 mm) deep (almost halfway through the pipe wall) and adjacent to the other alloy 625 pipe section. Stray current corrosion would most likely occur on the alloy 625 end of the longest isolated pipe section and un-

der flow conditions where galvanic current was highest. It is, therefore, likely that the high propagation rate of this crevice corrosion was a result of stray current effects.

The section directly coupled to the alloy 625 under low flow experienced moderate corrosion near the alloy 625. It extended less than one pipe diameter along the pipe. The similar area in the pipe section at a 6-ft/s (2-m/s) flow also experienced moderate corrosion, but the corrosion extended 2 in. past the flange weld or about two to three pipe diameters along the pipe. Corrosion at the other end of the pipe section away from the alloy 625 was insignificant.

Corrosion of the copper-nickel section of the Aeroquip RISIC and the associated copper-nickel pipe at 6 ft/s (2 m/s) was difficult to assess but appeared to be slight to moderate. Corrosion products were visible for some distance along the pipe, indicating that corrosion was not localized near the alloy 625. Under low flow, the copper-nickel section of the Aeroquip RISIC showed some corrosion with estimated depths of 2 to 5 mils (0.03 to 0.05 mm). The associated copper-nickel pipe section experienced shallow corrosion near the RISIC. The copper-nickel section of the Murdock RISIC at 6 ft/s (2 m/s) showed moderate corrosion for about one pipe diameter adjacent to the flange but little corrosion near the titanium interface. This was somewhat unexpected because galvanic corrosion should be greatest near the noble metal. The associated copper-nickel pipe section showed significant corrosion in the weld areas and the heat-affected zone of the flange connecting to the RISIC.

The 1-ft (0.3-m) copper-nickel separator section experienced little corrosion under low flow, while the coupled copper-nickel pipe exhibited pitting and corrosion up to 8 in. (four pipe diameters) "downstream" of the separator. Wall thinning of the copper-nickel pipe associated with the 1-ft (0.3-m) alloy 625 separator was 21 mils (0.54 mm) near the separator, with pits of 10 to 52 mils (0.25 to 1.2 mm). This corrosion was visible up to 12 diameters along the pipe. Under 6 ft/s (2 m/s) flow, the copper-nickel separator showed up to 3 mils (0.08 mm) of wall thinning, while the coupled piping showed thinning of 15 mils (0.29 mm). Piping associated with the alloy 625 separator was thinned about the same (16 mils [0.32 mm]) near the separator, with corrosion extending one or two pipe diameters along the pipe.

The 3-ft copper-nickel separator section experienced deep pitting and corrosion on the end closest to the alloy 625. Wall thickness losses of 7 to 26 mils (0.18 to 0.67 mm) were measured. The associated coupled copper-nickel pipe had shallow to deep craters up to six diameters along the pipe. The coupled copper-nickel pipe associated with the 3-ft (1-m) alloy 625 separator experienced only light to moderate corrosion. Corrosion here extended up to 24 in. (12 diameters) from the separator. Under a 6-ft/s (2-m/s) flow, the 3-ft (1-m) copper-nickel separator showed moderate corrosion on the end near the alloy 625, and the associated coupled copper-nickel pipe suffered slight to moderate corrosion. The copper-nickel pipe associated with the 3-ft (1-m) alloy 625 separator showed moderately deep corrosion near the separator and light to moderate corrosion at the opposite end where corrosion would not normally be expected.

The 10-ft (3-m) copper-nickel separator section experienced corrosion under low flow for at least 12 diameters adjacent to the alloy 625. Light corrosion was experienced by the copper-nickel coupled pipe associated with it for at least nine pipe diameters adjacent to the separator. The pipe associated with the 10-ft (3-m) alloy 625 separator had extensive corrosion, at least as deep as 30 mils (0.78 mm), extending at least 18 diame-

ters from the separator. At 6 ft/s (2 m/s), the 10-ft (3-m) copper-nickel separator and the associated coupled copper-nickel pipe adjacent to the separator experienced only light corrosion and surface cratering adjacent to the alloy 625. The copper-nickel pipe associated with the 10-ft (3-m) alloy 625 separator also experienced light corrosion.

The copper-nickel reducer for the 1.5-in. pipe exhibited nonuniform cratering at a 6-ft/s (2-m/s) flow up to 25 mils (0.64 mm) in depth. The pipe attached to the reducer showed only small, shallow craters. The reducer for the 1-in. pipe was also heavily corroded, with measured crater depths up to 30 mils (0.78 mm). Again, the attached pipe had little corrosion.

In general, the observations supported the results from the current and potential data. The effectiveness of the use of separators to reduce galvanic corrosion was obvious, and higher corrosion rates under low flow conditions were also apparent. Delocalization of corrosion was also apparent when long separators were used. The greater susceptibility of copper-nickel over alloy 625 to stray current corrosion was also observed. Differences in behavior due to separator material differences or differences in pipe diameter were not obvious after the 6-mo exposure.

1 Year Exposure

Observations of the pipe and RISIC sections after about 1 yr of exposure are presented in Appendix B. Observations were similar to those after 6 mo exposure, except they were greater in extent.

At the conclusion of the test, 18 in. (46 cm) of the copper-nickel pipes closest to the alloy 625 were cut off near the ends and cut in half longitudinally. An improvised pointed micrometer was used to measure wall thickness every 1/4 in. (0.6 cm) for the part of the pipe closest to the alloy 625 and every 1 in. (2.5 cm) farther away from the alloy 625. Twelve measurements were taken at each distance, and the results were averaged. These measurements showed considerable scatter. In addition, corrosion occurred on the outside of the pipe under the couplings for the first 2.5 in. (6.2 cm), frequently resulting in a groove at 2 to 2.5 in. (5.0 to 6.2 cm) on the outside of the pipe. The interpretation of the results was complicated by the two-sided corrosion over part of the pipe length, the presence of the corrosion groove, and the large amount of scatter in the measurements.

The results are shown in Figures 20 through 24. Figure 20 shows the measurements on the pipes directly coupled without the use of a separator or coupled using RISICs. The flange areas could not be measured, so the measurements started just past the weld where the flange was joined to the pipe. Corrosion of directly connected pipe, either with or without flow, was verified by these data. Pipe corrosion where RISICs were used was not obvious, in part because of the large distance from the alloy 625 before the first measurement was made.[f]

Figure 21 shows corrosion on the copper-nickel pipe as a function of the length and type of separator material used under low flow conditions. Corrosion near the alloy 625 extending one to two pipe diameters from the end closest to the alloy 625 was confirmed by these data. Although the electrochemical data and visual observations showed an effect of separator length and material, the measurements reported in Figure 21 cannot resolve these effects. Figure 22 shows similar information under flowing conditions.

[f]RISIC length plus flange length, totaling about 5 in. [12cm].

These data show that the maximum depth of corrosion appears similar in all cases, contrary to the visual and electrochemical data. The longest separators resulted in corrosion extending up to four diameters from the end closest to the alloy 625, the intermediate length separators resulted in corrosion extending three diameters, while the shortest separators showed corrosion extending only one to two diameters. These are consistent with the electrochemical and visual data.

Corrosion on the copper-nickel separators is shown in Figure 23. This corrosion was primarily because of stray current corrosion from the potential field set up by the alloy 625 on one side of the separator and the copper-nickel on the other side. The longest separator under flowing conditions shows more corrosion, consistent with the larger driving force for stray current corrosion and with the electrochemical and visual data. Other differences in separator performance were less significant and somewhat obscured by the data scatter, although maximum depths of corrosion appeared related to separator length, consistent with the other observations.

Figure 24 shows the effect of size of the copper-nickel pipe on corrosion. Measurements could not be taken on the copper-nickel reducers closest to the alloy 625, so the first measurements were about 2.5 in. (6.2 cm) from the alloy 625 on these pipes. Maximum depth of corrosion and overall corrosion were greatest on the smallest pipe, as expected. It was difficult to distinguish differences in the amount of corrosion between the medium sized pipe and the largest pipe because of data scatter. It is possible that the greatest differences in behavior occurred within the flanges, the RISICs, and the reducers and were, therefore, not observable for that reason.

In summary, the pipe measurements were generally supportive of the electrochemical and visual data, although they were not as accurate.

CONCLUSIONS

Separators can significantly reduce galvanic corrosion of 2-in. copper-nickel pipe coupled to alloy 625 pipe, with 3 to 10 ft (1 to 3 m) being optimum. The effect of the separators was maximum under low flow conditions where the galvanic corrosion was greatest. Alloy 625 separators were more effective than copper-nickel separators at lowering galvanic corrosion and were less susceptible to stray current corrosion. Delocalization of corrosion occurred when long separators were used, making maximum penetration depth less for a given amount of metal loss. Longer separators had a greater tendency to undergo stray current corrosion, with stray current-induced crevice corrosion being the primary corrosion mode for alloy 625 separators. Smaller diameter copper-nickel pipe experienced higher corrosion rates than larger diameter pipe when coupled to 2-in. alloy 625 piping. Linearity of potential profile through the separators was an accurate indicator of whether stray current corrosion was taking place. In general, visual observations, current data, and potential data were all in agreement.

RECOMMENDATION

The Navy should use 3-ft (1-m) titanium separator pipes, electrically isolated at both ends, to minimize galvanic corrosion in 2-in.-diameter dissimilar metal seawater piping joints.

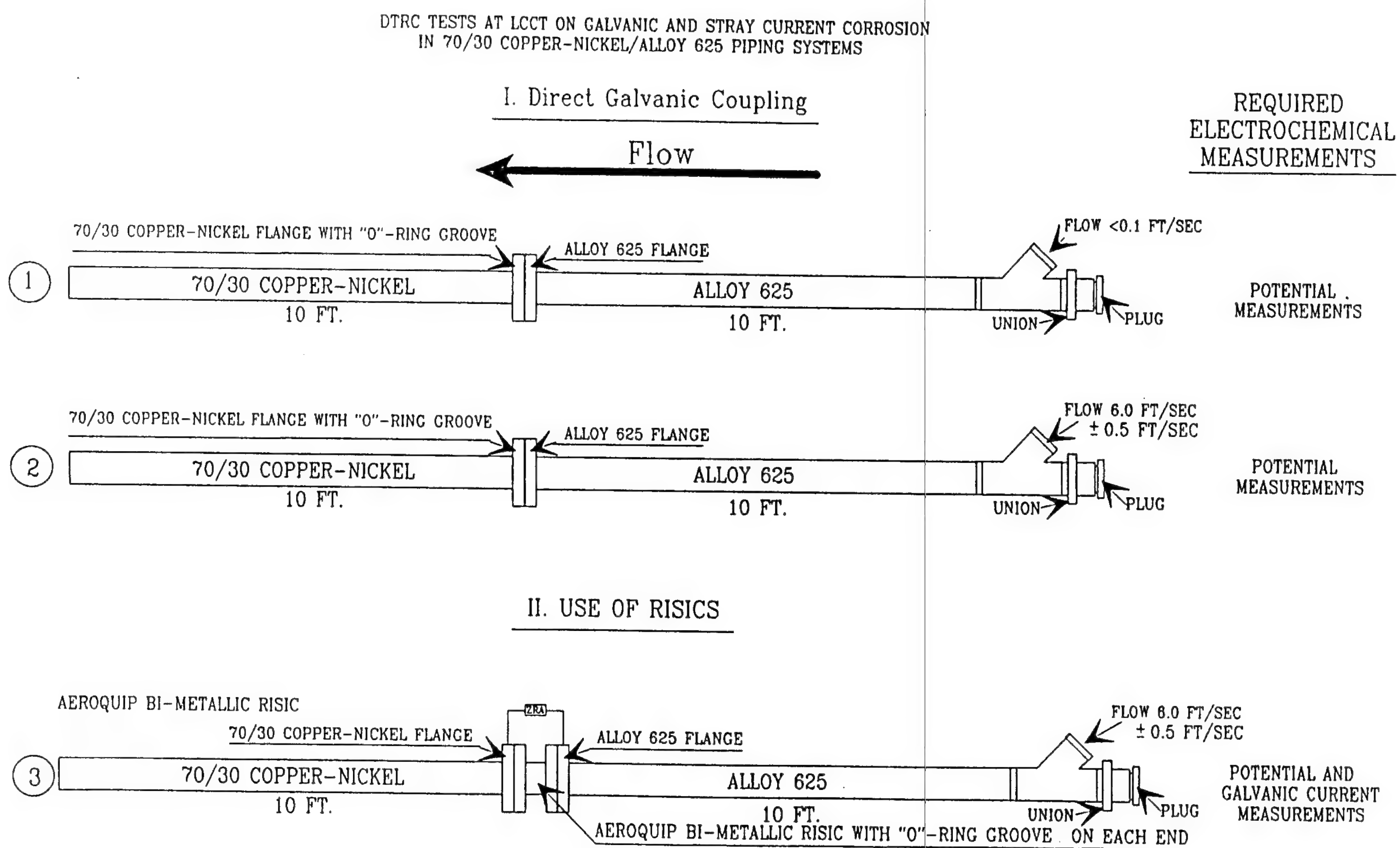


Figure 1a. Nos. 1 through 3.

Figure 1. Piping mockups.

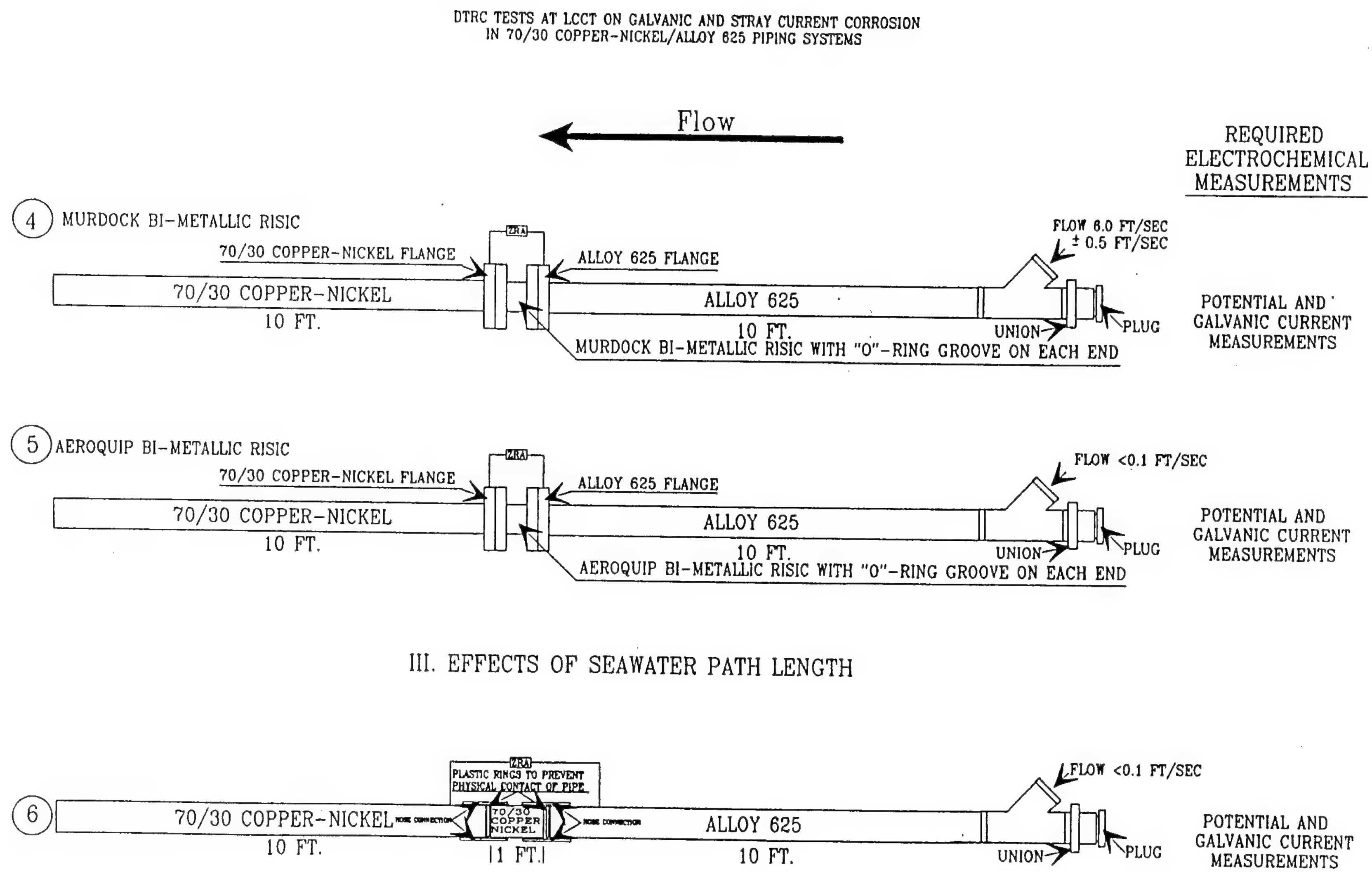


Figure 1b. Nos. 4 through 6.

Figure 1. Piping mockups.

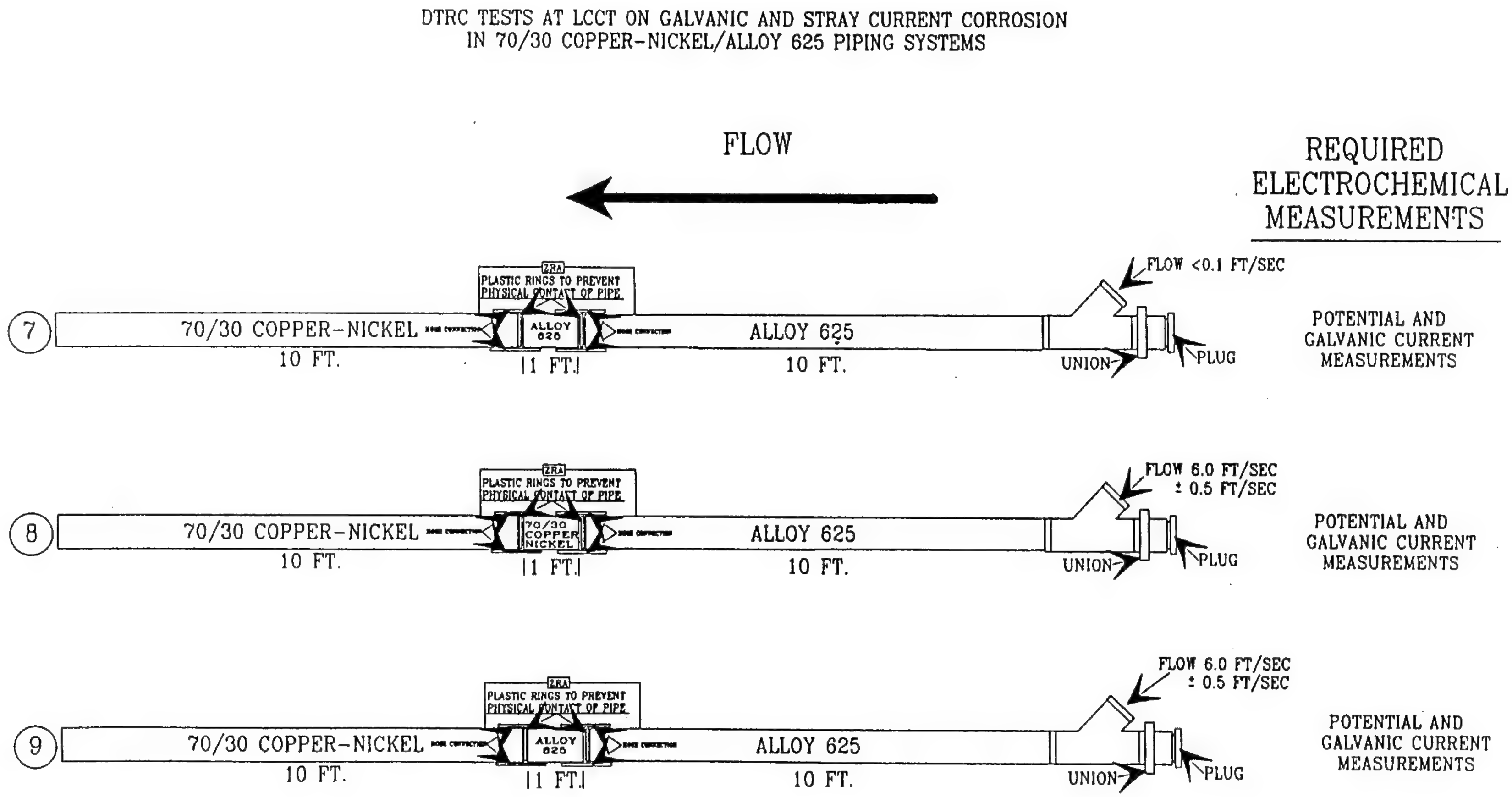


Figure 1c. Nos. 7 through 9.

Figure 1. Piping mockups.

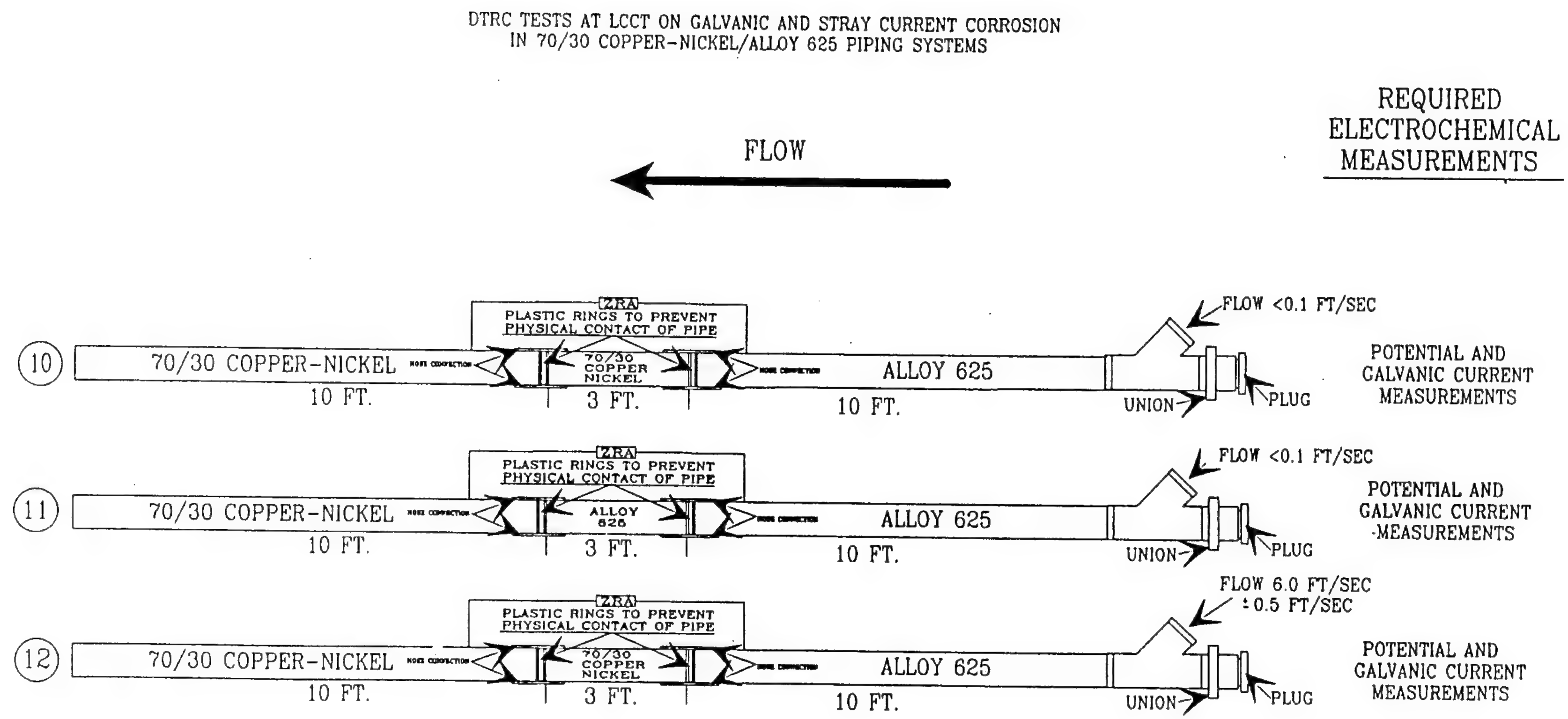


Figure 1d. Nos. 10 through 12.

Figure 1. Piping mockups.

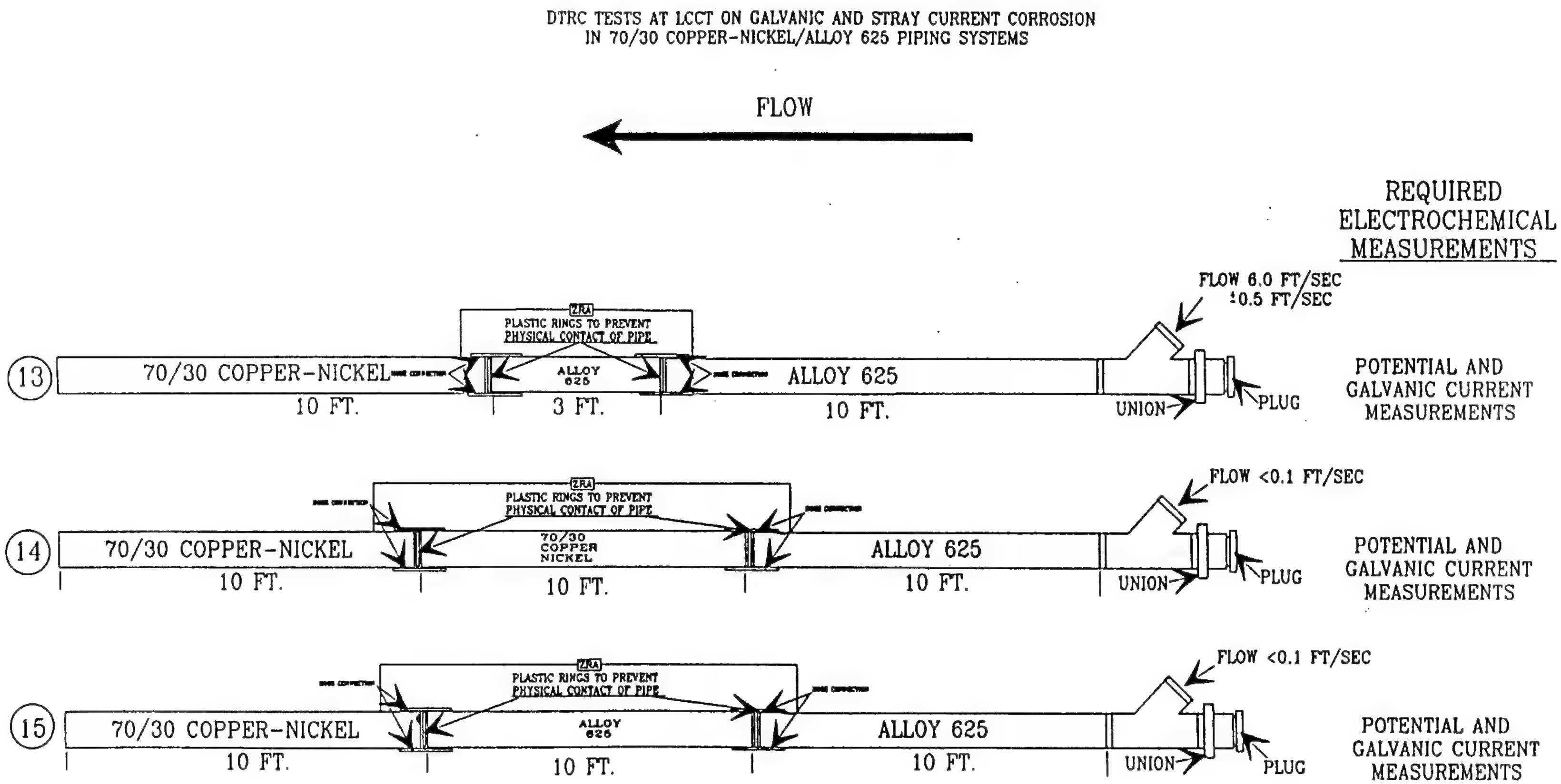


Figure 1e. Nos. 13 through 15.

Figure 1. Piping mockups.

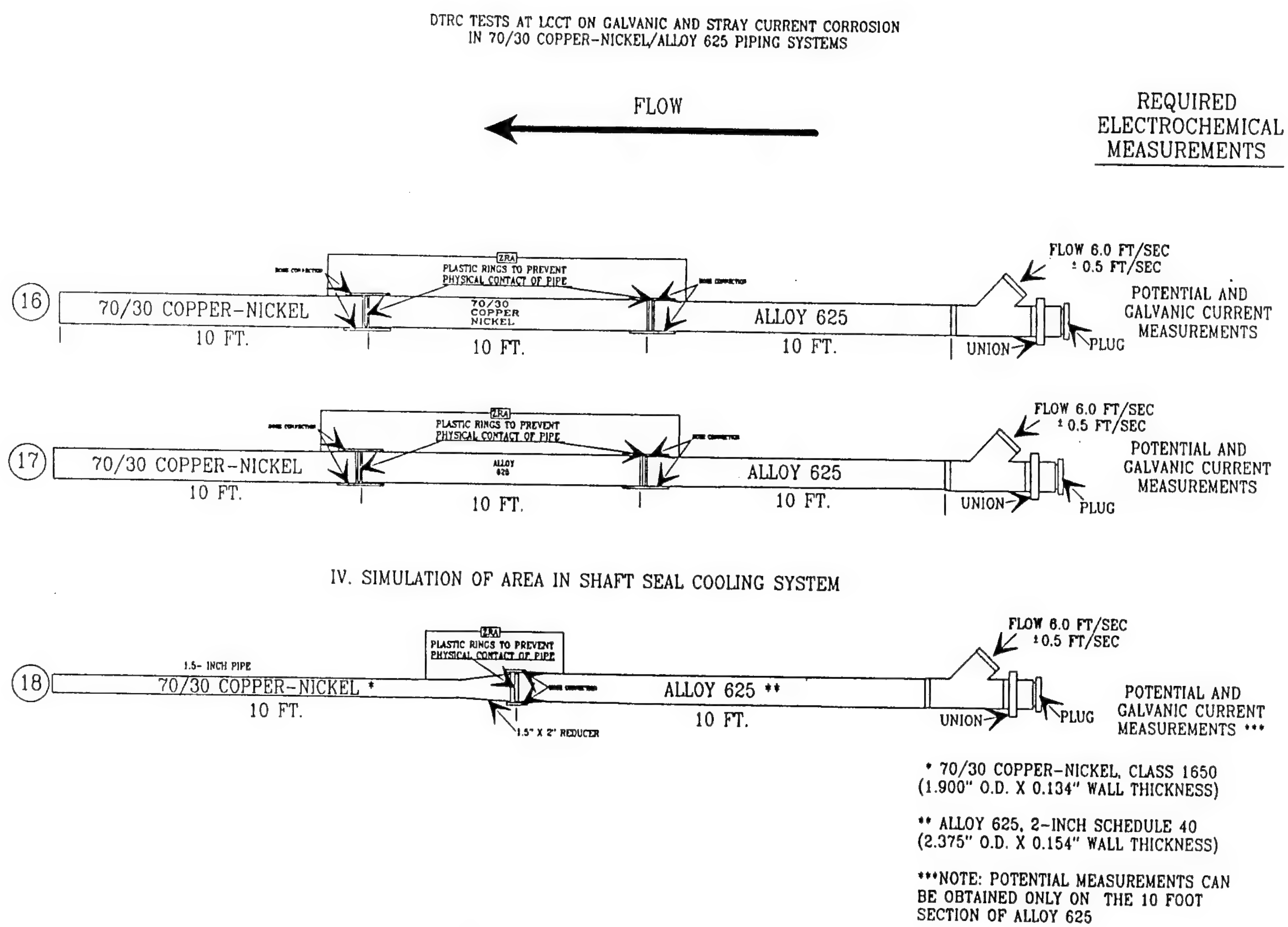


Figure 1f. Nos. 16 through 18.

Figure 1. Piping mockups.

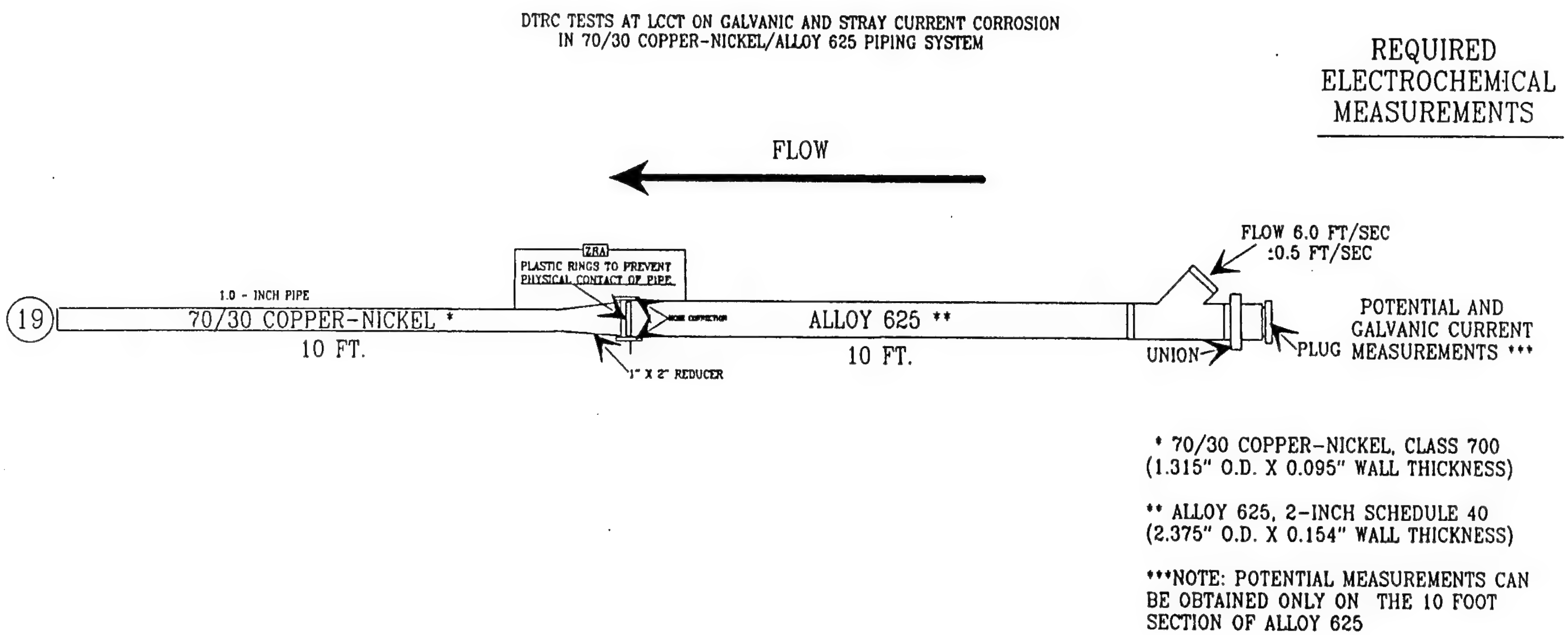
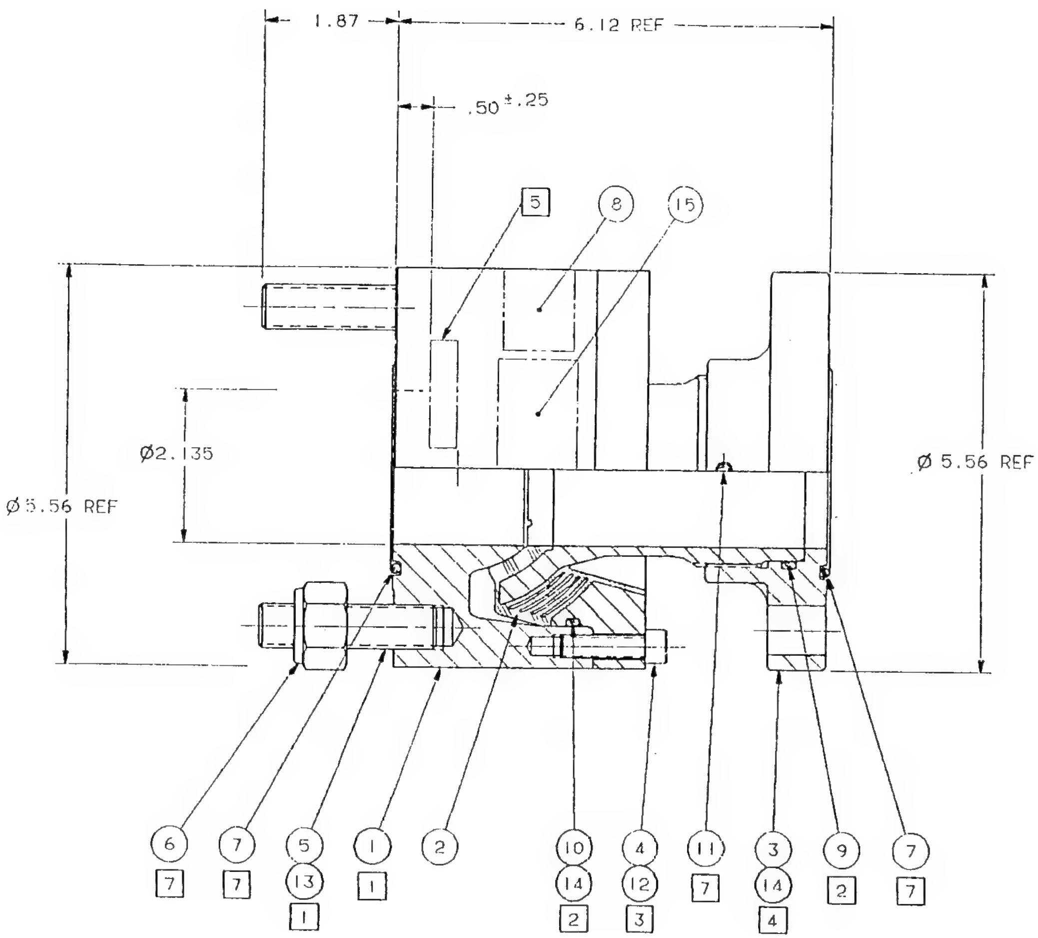


Figure 1g. No. 19.

Figure 1. Piping mockups.



NOTES:

1. APPLY ITEM 13 TO THE THREADS OF ITEM 1 AND 5 AND INSTALL ITEM 5 TO STANDOUT DIMENSION SHOWN.
2. LUBRICATE O-RINGS AND MATING SURFACES WITH ITEM 14 PRIOR TO INSTALLATION.
3. LUBRICATE SCREWS WITH ITEM 12 AND TORQUE TO 125 ± 10 INCH POUNDS.
4. LUBRICATE THREADS WITH ITEM 14 PRIOR TO ASSEMBLY.
5. DIE STAMP (0.25 CHARACTERS) 2" CONNECTOR CODE I.D. 27826 PART NO. DASH NO. AND SERIAL NO. IN NOTED LOCATION USING LOW STRESS DIES.
6. PRESSURE TEST EACH ASSEMBLY TO 1050 +50/-0 PSIG FOR 2 TO 5 MINUTES. TEST PRESSURE IS FOR THIS COMPONENT ONLY. THE SYSTEM TEST PRESSURE, WHEN THIS COMPONENT IS INSTALLED, SHALL BE IN ACCORDANCE WITH THE APPLICABLE SYSTEM DIAGRAM.
7. ITEMS 6, 7 AND 11 ARE TO BE INSTALLED DURING SYSTEM INSTALLATION
8. THIS EQUIPMENT IS SIMILAR IN DESIGN, CONSTRUCTION AND INTENDED SERVICE TO THAT EQUIPMENT DEPICTED ON MEC DRAWING 299947 WHICH HAS BEEN ACCEPTED AS MEETING ALL THE HI-SHOCK REQUIREMENTS IN ACCORDANCE WITH MIL-S-901C FOR MEDIUM WEIGHT, GRADE "A" SHOCKPROOF EQUIPMENT AS FOLLOWS: EQUIPMENT CLASS I, MOUNTING FIXTURE 9. DTNSRDC/A TEST ACTIVITY, REPORT NO TM-27-76-35 DATED 23 SEP 76. QUALIFICATION OF UNIT APPROVED BY NAVSEA LETTER PMS 393/CK SSN688 CL/(9480-0) SER 4486 DATED 2FEB78.
9. SEE DRAWING 302676 FOR PARTS OF SEAL ASSEMBLY THAT ARE LEVEL I.
10. ADEQUATE STRENGTH OF THESE COMPONENTS HAS BEEN DEMONSTRATED AS MEETING THE REQUIREMENTS OF THE SUBMARINE SAFETY DESIGN REVIEW PROCEDURES MANUAL BY BEING QUALIFIED IN ACCORDANCE WITH THE REQUIREMENTS OF NAVSEA LETTER PMS 393/CK SSN688 CL/(9480-0) SER 1706 OF 20 OCT,1975.
11. THIS EQUIPMENT IS ESSENTIALLY IDENTICAL IN DESIGN, CONSTRUCTION, AND WEIGHT TO THAT SHOWN ON MEC DRAWING NUMBER 299947 WHICH HAS BEEN ACCEPTED AS MEETING THE VIBRATION REQUIREMENTS OF MIL-STD-167B AS MODIFIED ABOVE PER TM-27-76-35 DATED 23 SEP 76.
12. KEY FLANGE DIMENSIONS ARE IN ACCORDANCE WITH BUSHIPS DWG. 810-1385861H.
13. SEALANT SHALL BE APPLIED IN ACCORDANCE WITH THE MANUFACTURE'S PROCEDURE.
14. WHEN THIS ASSEMBLY IS REVISED, CDS DRAWING 302677 SHALL ALSO BE REVISED.

Figure 2. Murdock type 1 RISIC–2A.

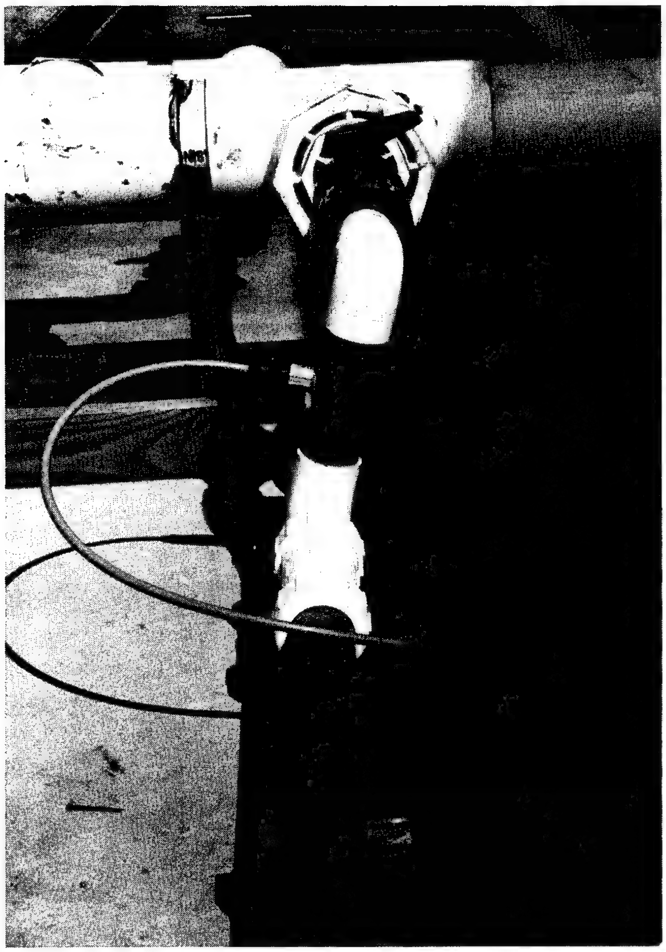


Figure 3. Main seawater supply line to mockups.

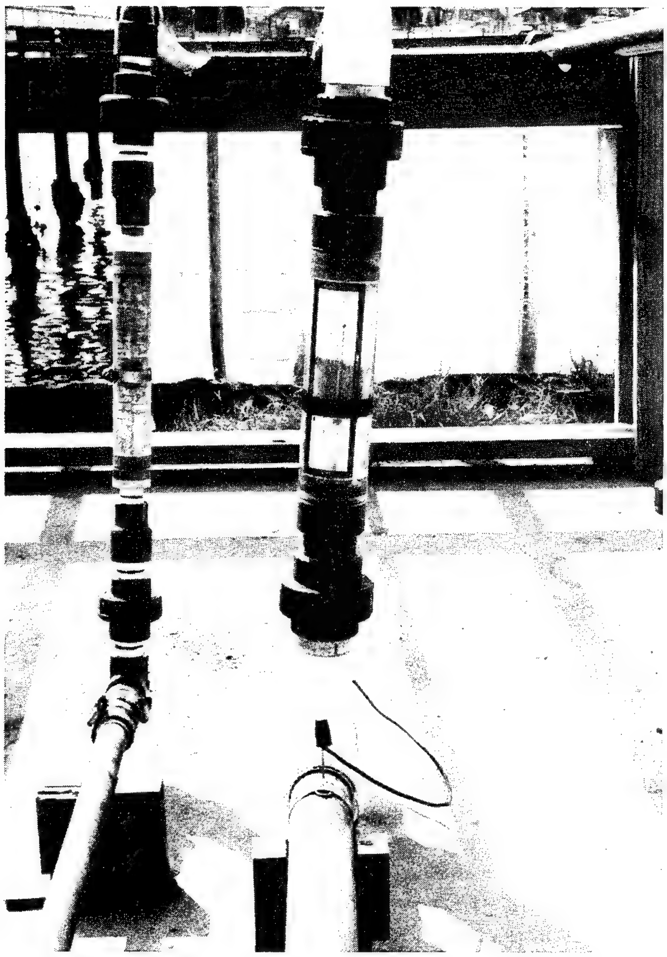


Figure 4. Rotameter in discharge end of mockup.

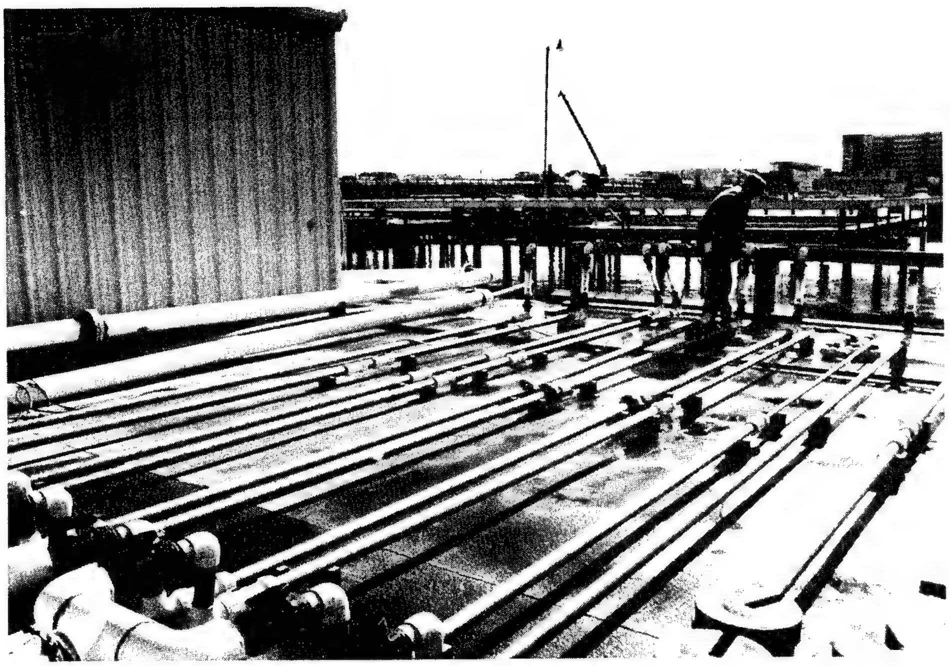


Figure 5. Overall view of mockups under construction.

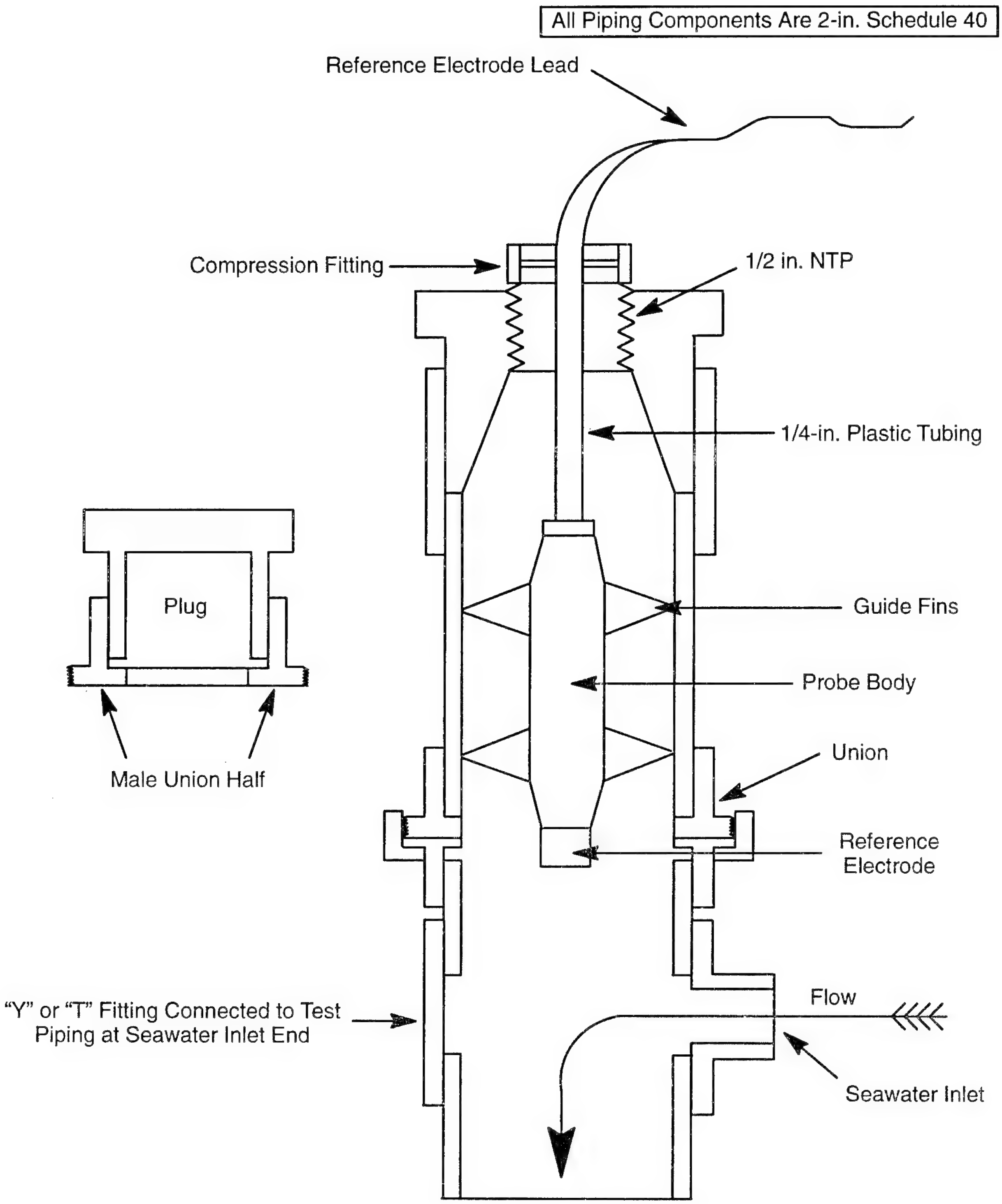


Figure 6. Potential measuring probe.

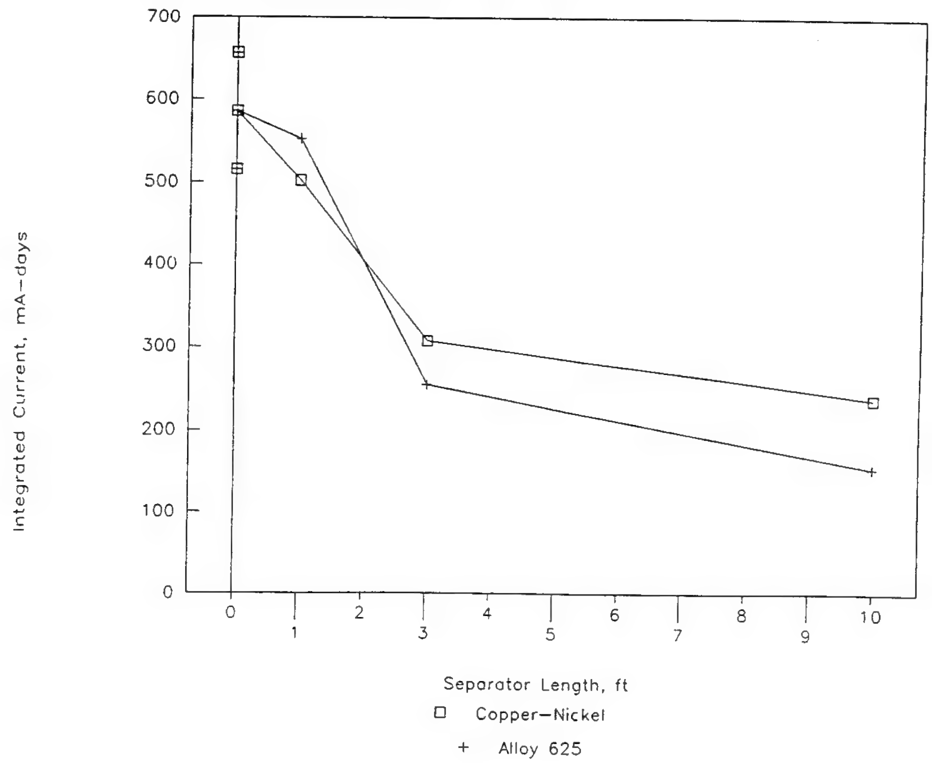


Figure 7. Effect of separator length over first 6 mo exposure (6 ft/s [2 m/s]).

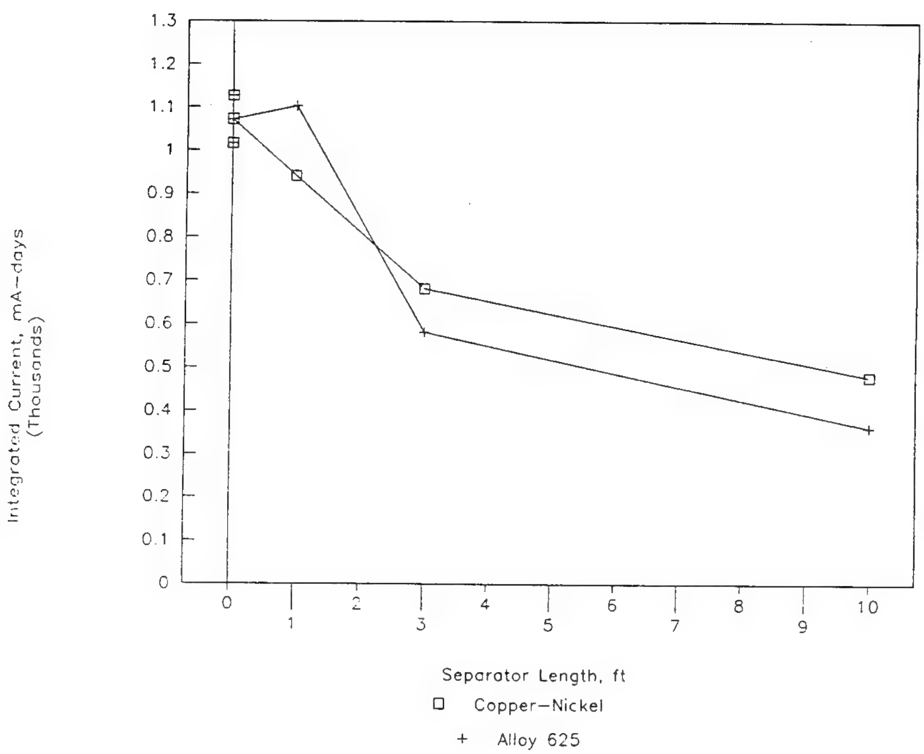


Figure 8. Effect of separator length over 1 yr exposure (6 ft/s [2 m/s]).

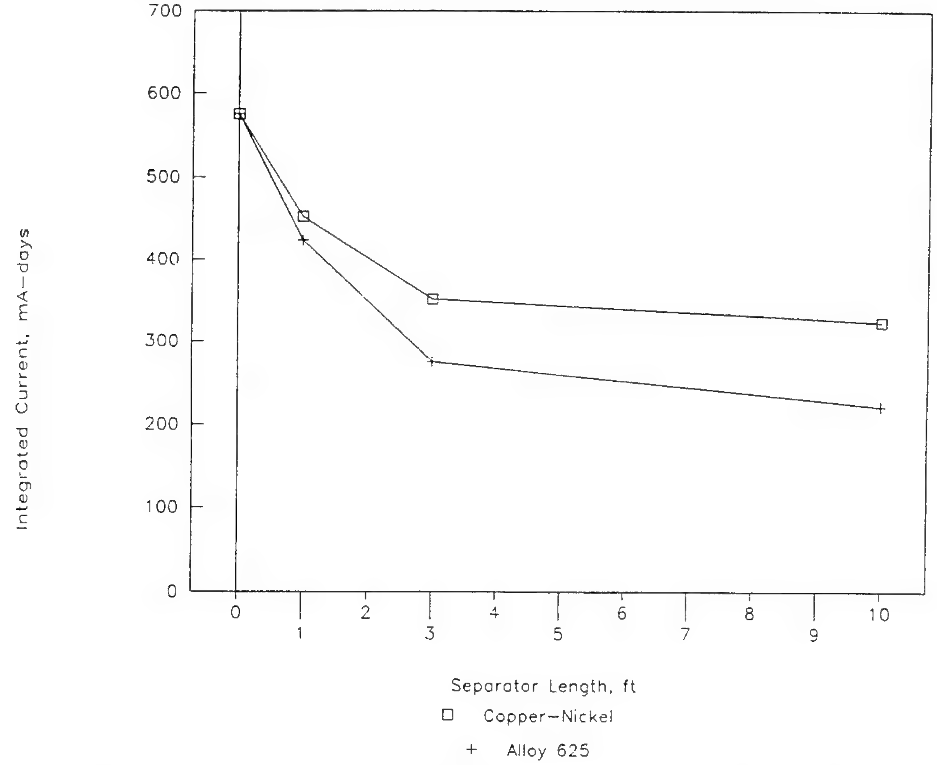


Figure 9. Effect of separator length over first 6 mo exposure (less than 1 ft/s [0.3 m/s]).

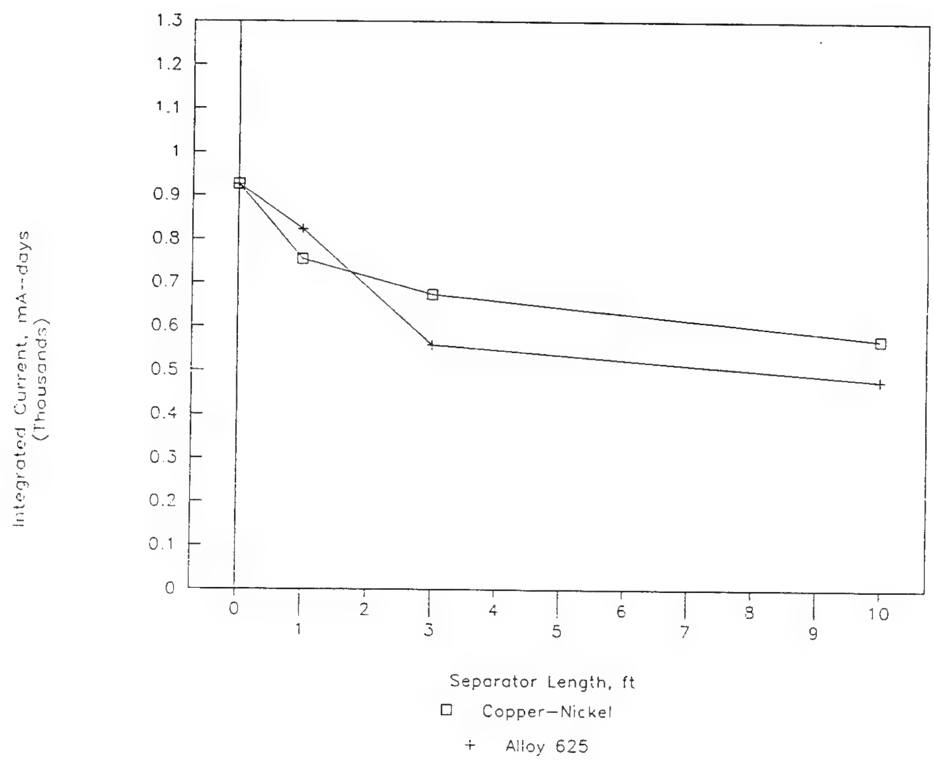


Figure 10. Effect of separator length over 1 yr exposure (less than 1 ft/s [0.3 m/s]).

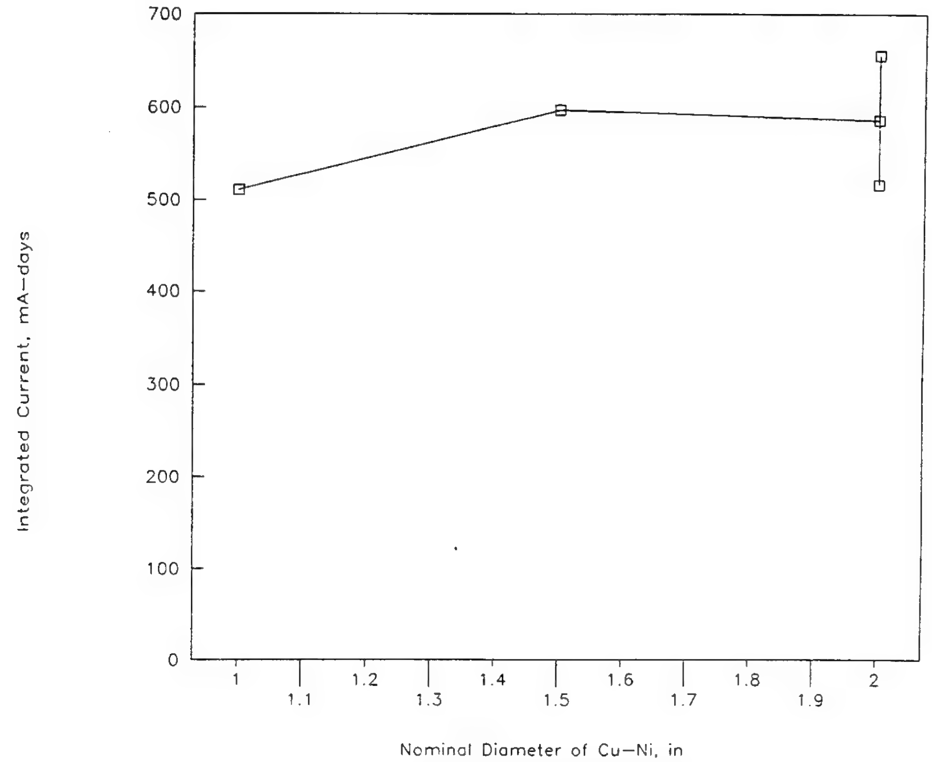


Figure 11. Effect of diameter over first 6 mo exposure (6 ft/s [2 m/s]).

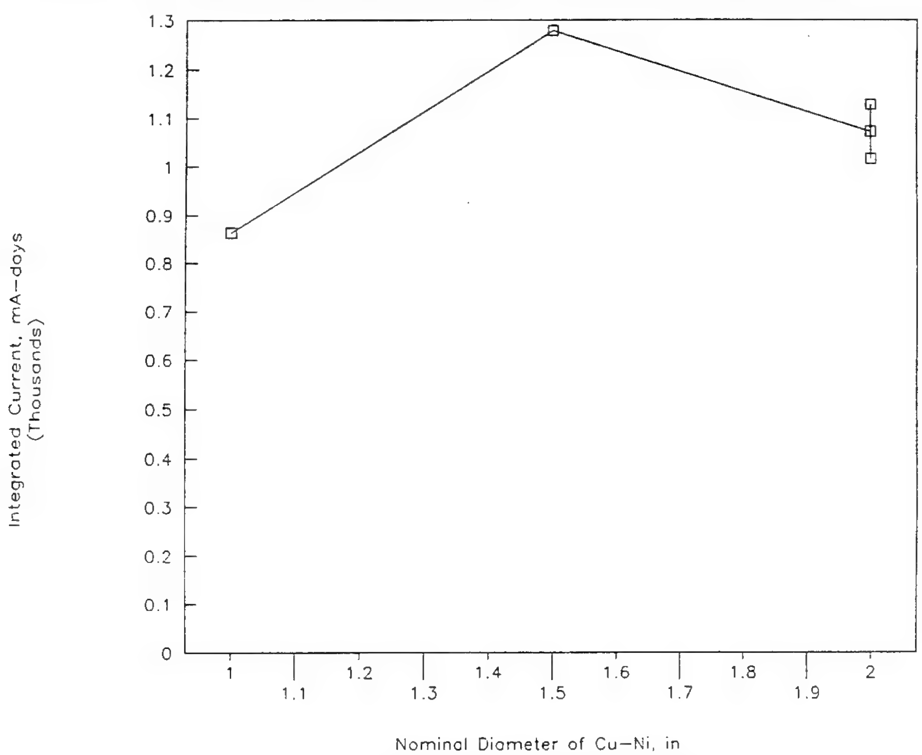


Figure 12. Effect of diameter over 1 yr exposure (6 ft/s [2 m/s]).

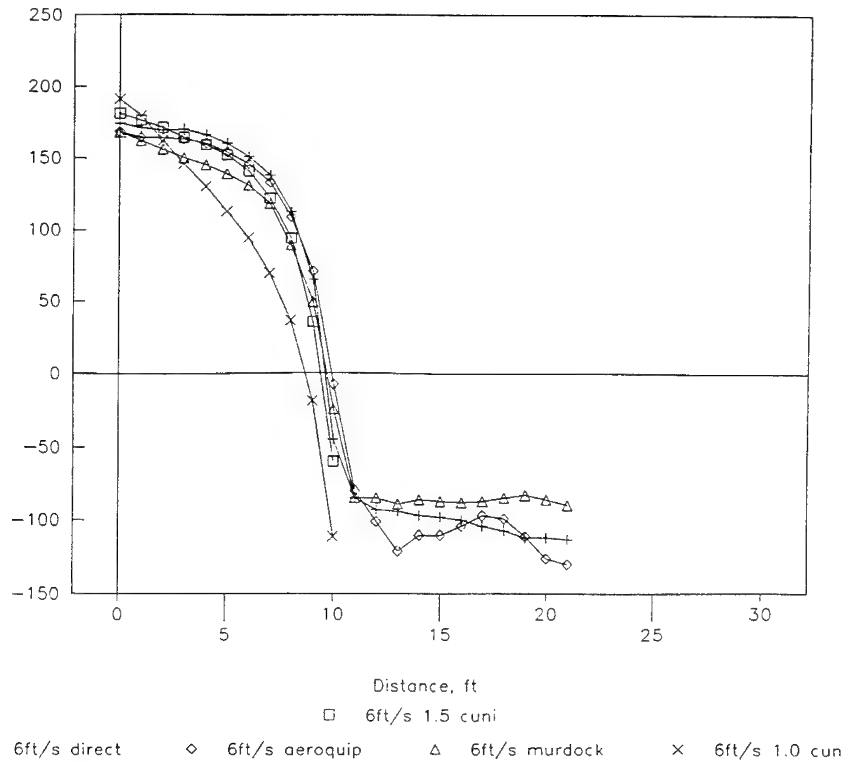


Figure 13. Potential profiles of all mockups without separators after 6 mo exposure (6 ft/s [2 m/s]).

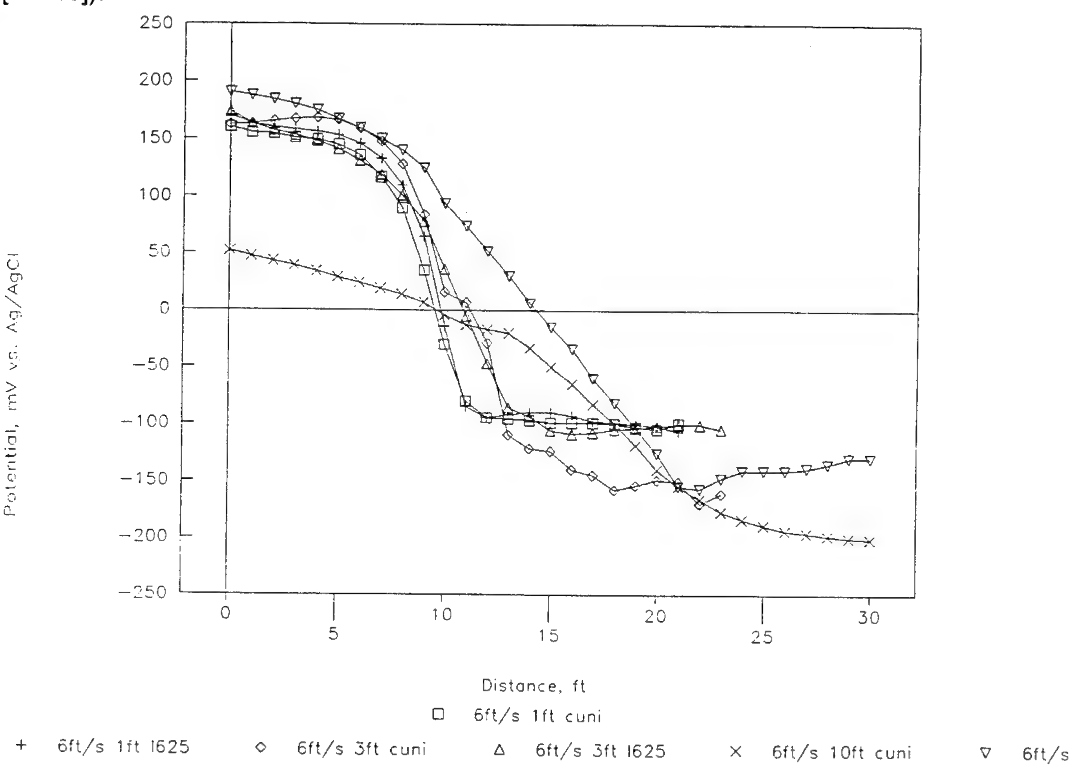


Figure 14. Potential profiles of all mockups with separators after 6 mo exposure (6 ft/s [2 m/s]).

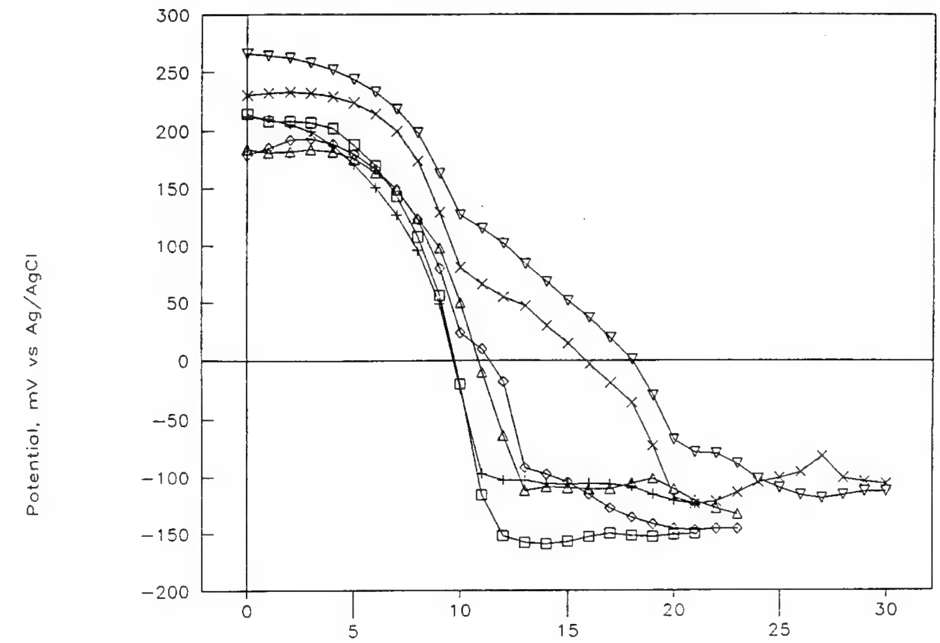


Figure 15. Potential profiles of all mockups with separators after 6 mo exposure (less than 1 ft/s [0.3 m/s]).

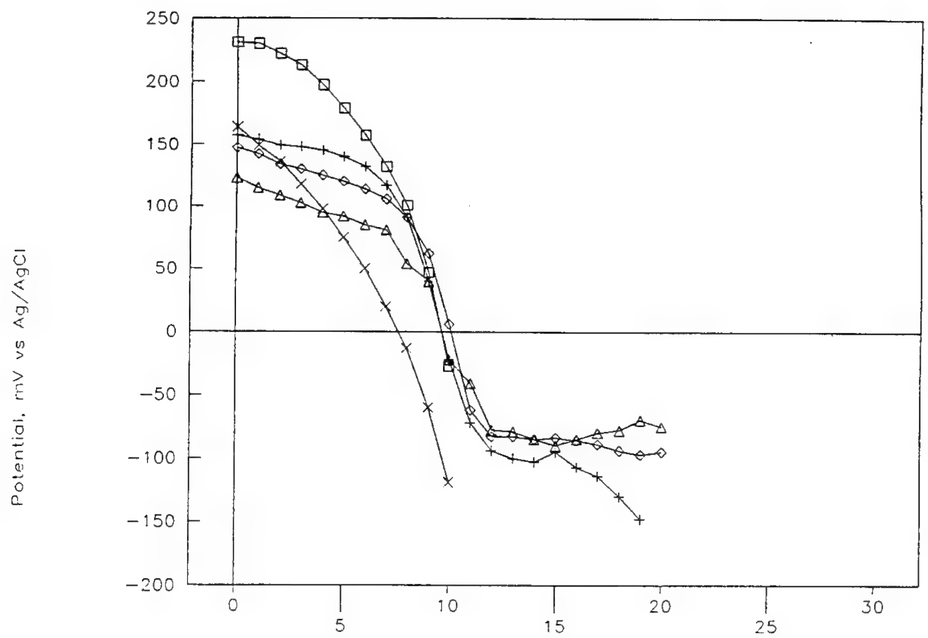


Figure 16. Potential profiles of all mockups without separators after 1 yr exposure (6 ft/s [2 m/s]).

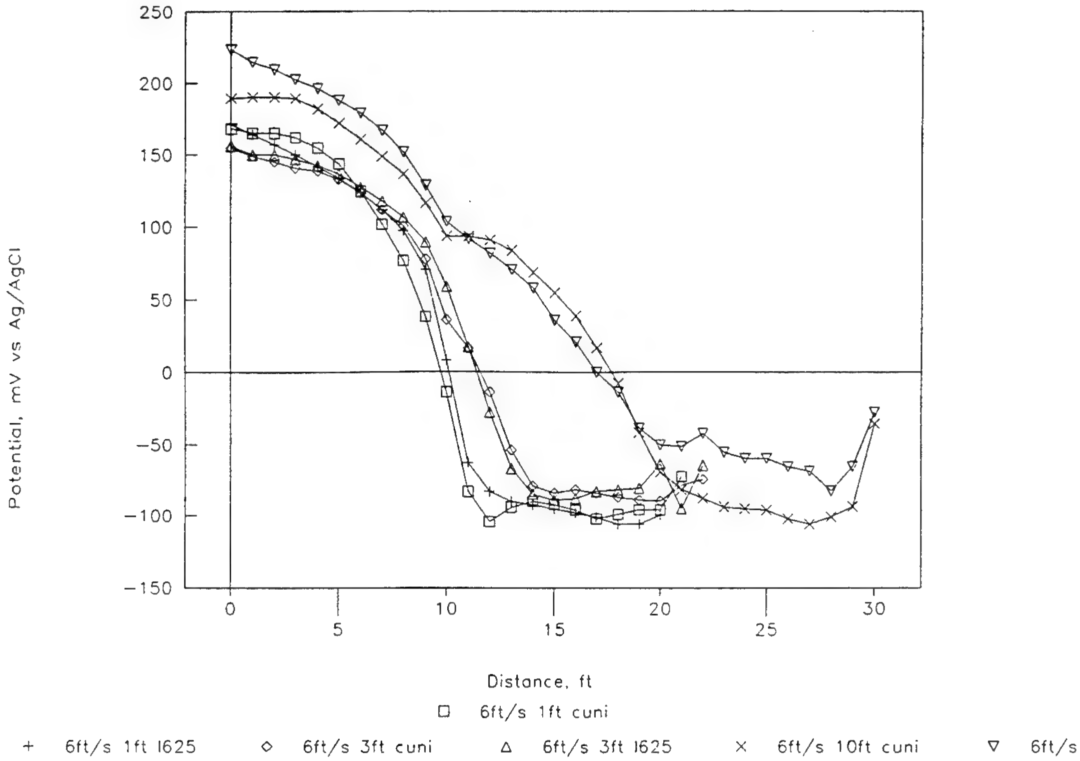


Figure 17. Potential profiles of all mockups with separators after 1 yr exposure (6 ft/s [2 m/s]).

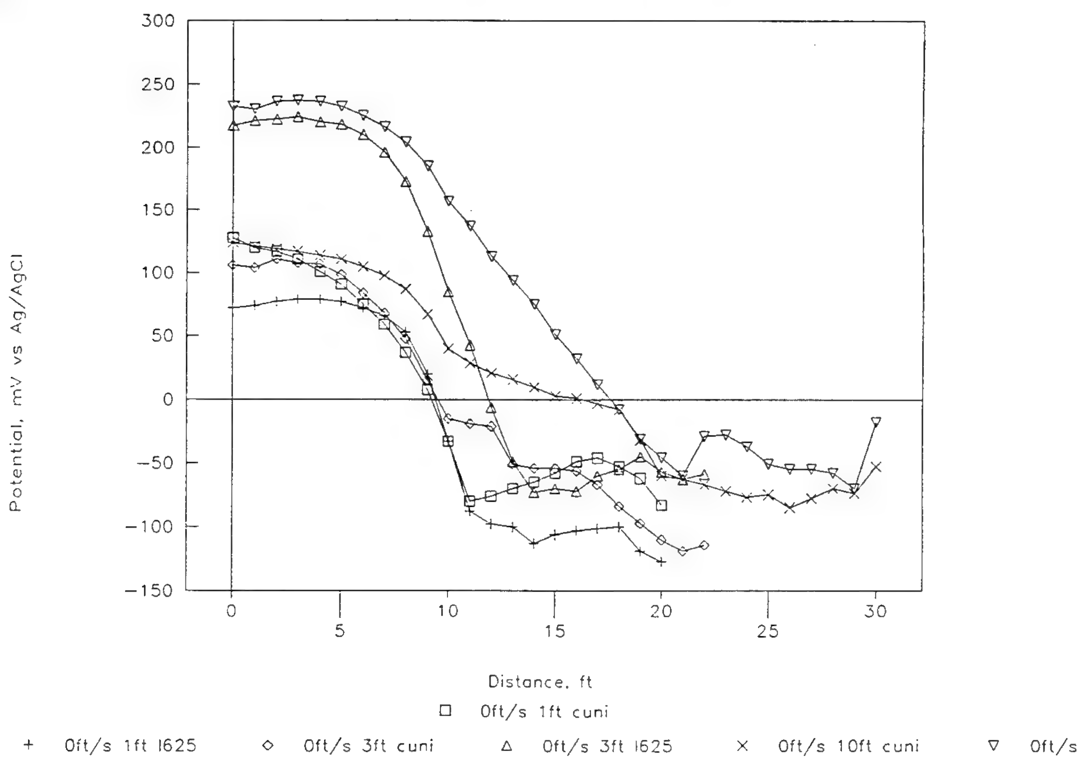


Figure 18. Potential profiles of all mockups with separators after 1 yr exposure (less than 1 ft/s [0.3 m/s]).

Figure 19. Crevice corrosion on alloy 625 pipe exterior after 6 mo exposure, isolated section, less than 1 ft/s [0.3 m/s], end nearest alloy 625.

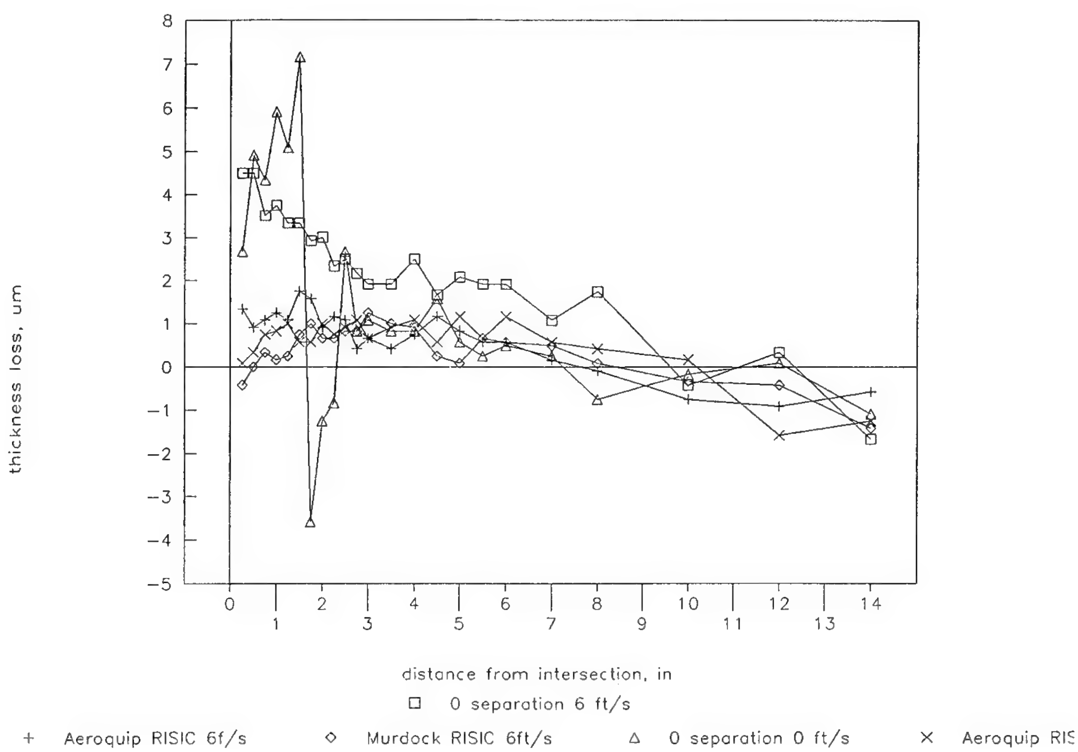


Figure 20. Thickness loss measurements for pipes coupled directly or using RISICs.

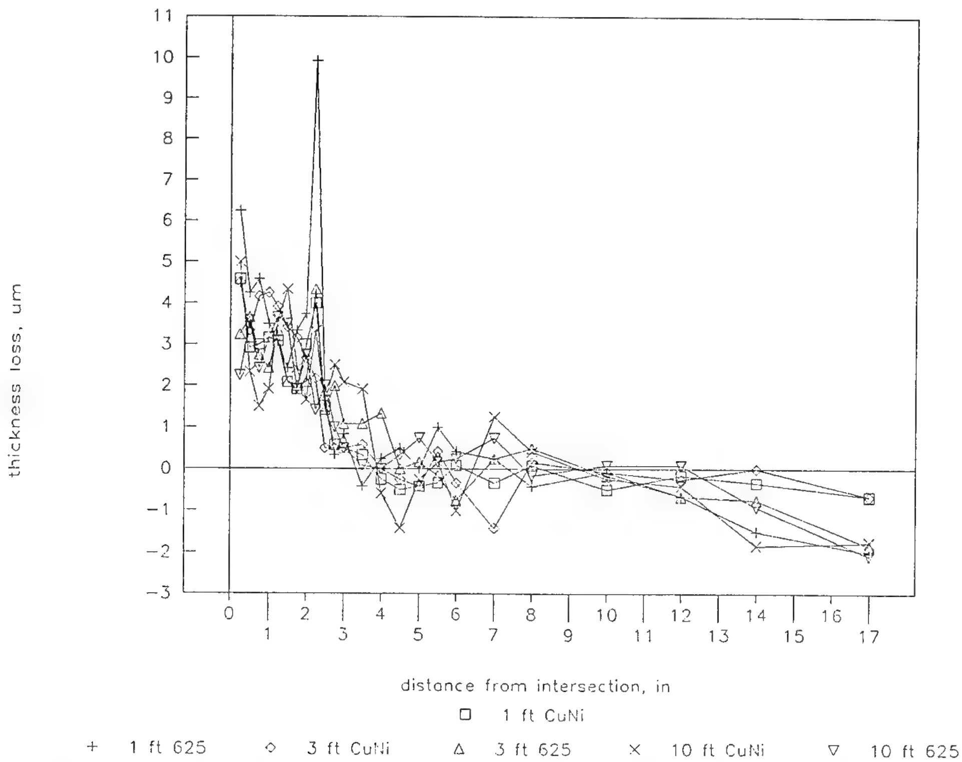


Figure 21. Thickness loss measurements for pipes coupled using separators less than 1 ft/s (0.3 m/s).

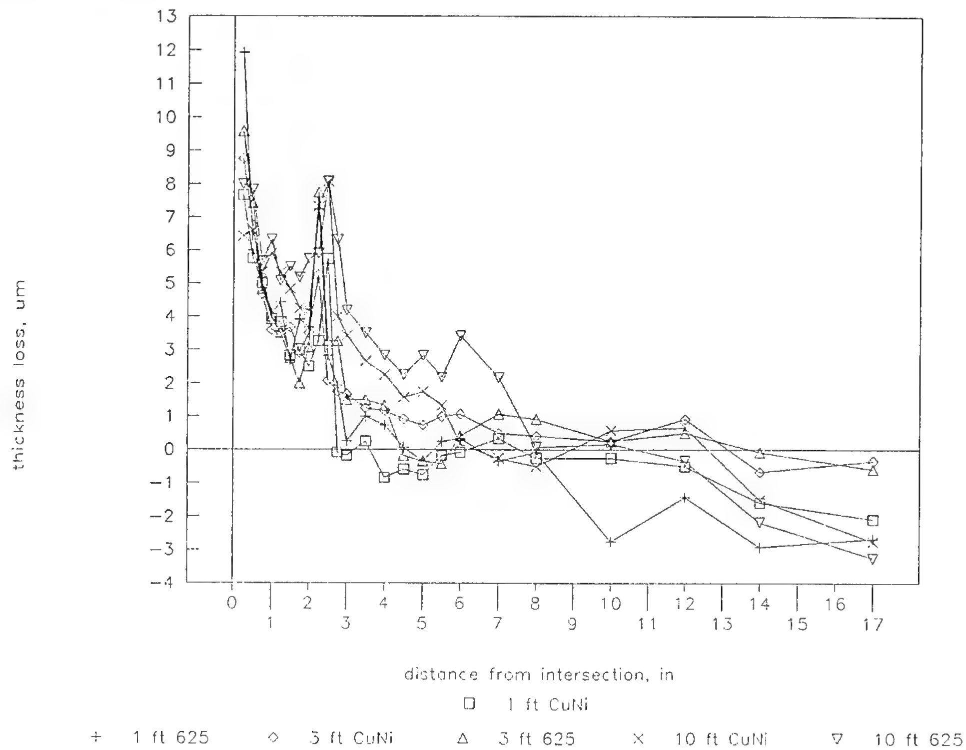


Figure 22. Thickness loss measurements for pipes coupled using separators 6 ft/s (2 m/s).

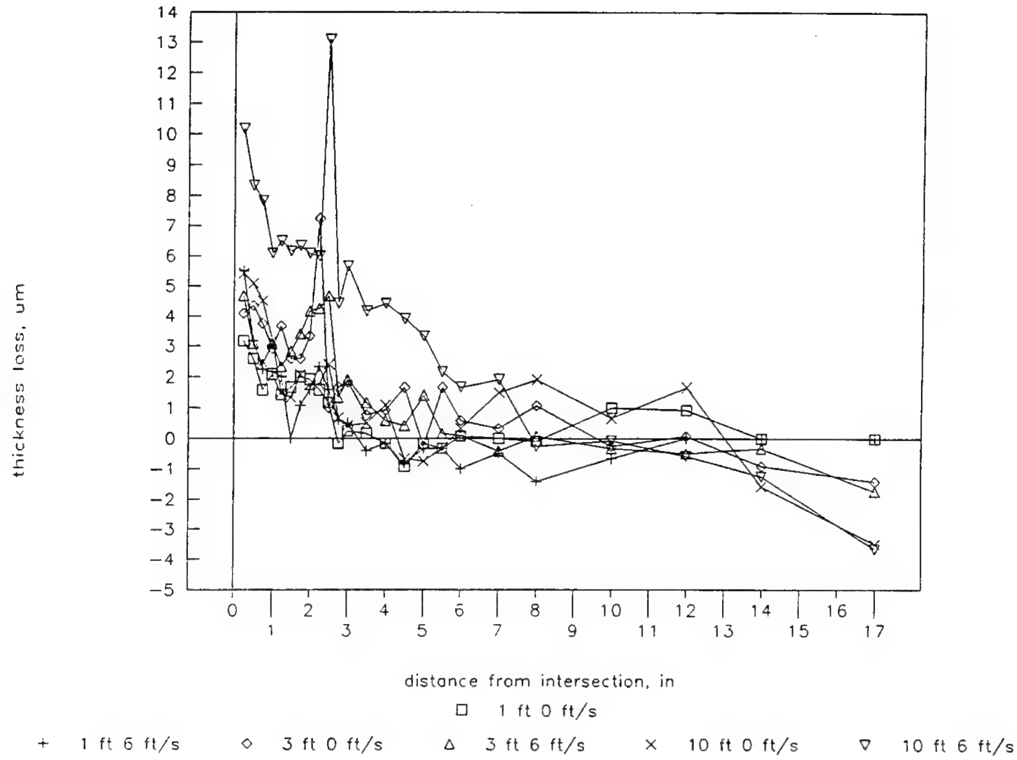


Figure 23. Thickness loss measurements for copper-nickel separator pipes.

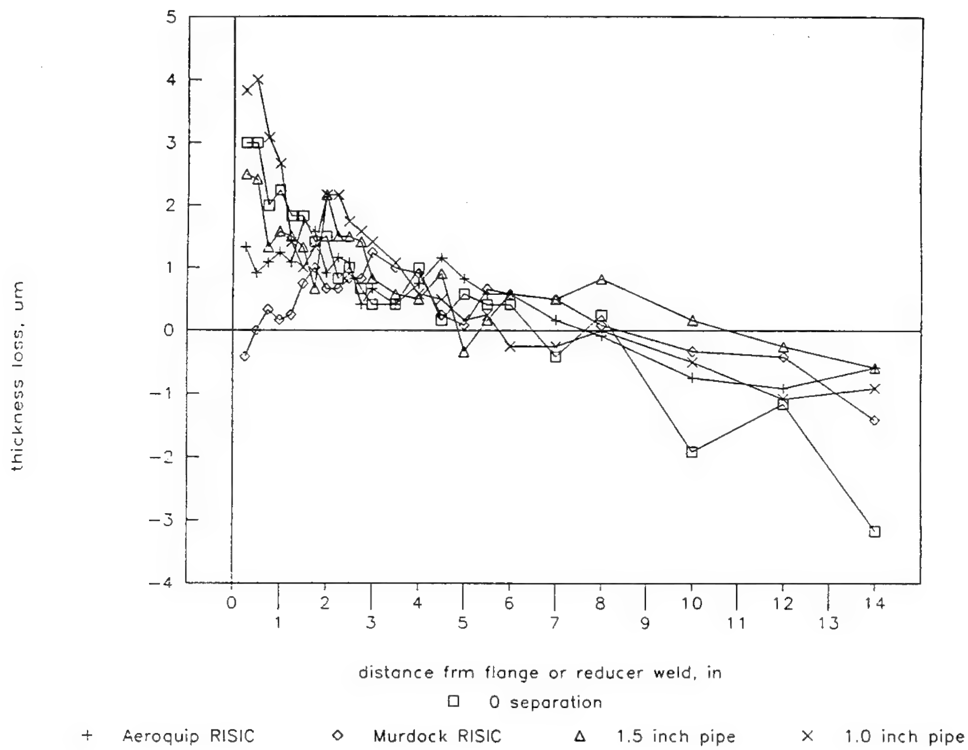


Figure 24. Thickness loss measurements for pipes of various diameters compared to pipes coupled directly or using RISICs.

Table 1. Compositions and properties of tested materials.

Alloy	Copper-Nickel	Copper-Nickel	Copper-Nickel	Copper-Nickel	Alloy 625	Alloy 625
Supplier	Tioga Pipe Supply Co., Inc.	Tioga Pipe Supply Co., Inc	Wolverine Tube	Newman Flange & Fitting Co.	Haynes International, Inc.	Newman Flange & Fitting Co.
Heat or Lot	Order A36442	Heat FQ Lot WO323683	Part 609921	Heat FF–61	Heat 2650–0–6782	Heat MM–27
Form	2-in. Pipe	1.5-in. Pipe	1-in. Pipe	2-in. Flange	2-in. Pipe	2-in. Flange
Cu	67.86	67.88	68.9	68.19	–	–
Ni	30.34	30.41	30.1	30.8	60.00	60.47
Fe	0.93	0.85	0.56	0.54	4.30	4.49
Mn	0.74	0.70	0.56	0.41	0.24	0.10
Zn	0.46	0.053	0.09	0.02	–	–
C	0.030	0.038	0.021	0.013	0.02	0.03
S	0.016	0.016	0.008	0.002	<0.002	0.003
P	0.006	<0.01	0.015	0.001	<0.005	0.011
Pb	0.002	<0.01	0.008	0.006	–	–
Ti	–	–	–	–	0.31	0.18
Si	–	–	–	–	0.22	0.13
Nb+Ta	–	–	–	–	3.42	3.49
Mo	–	–	–	–	8.87	8.98
Cr	–	–	–	–	21.62	21.71
Co	–	–	–	–	0.13	0.14
Al	–	–	–	–	0.18	0.27
			Mechanical Properties			
Ultimate Tensile Stress (KSI)	60.4	59.6	61.2	62.1	139.9	135.0
Yield Stress (KSI)	22.5	23.4	29.1	41.6	68.2	63.0
Elong in 2 in. (%)	45.5	45	47	37.50	45.5	47.0

Table 2. Measured currents.

		mA Test Pipe Designation								
Date	Days	3	4	5	6	7	8	9	10	11
3/11/91	4	-0.043	-0.021	-0.036	-0.007	-0.051	-0.042	-0.007	-0.008	-0.021
3/12/91	5	-0.025	-0.064	-0.004	-0.047	-0.032	-0.053	-0.044	-0.029	-0.029
3/13/91	6	-0.044	-0.049	-0.043	-0.057	-0.042	-0.028	-0.009	-0.031	-0.037
3/14/91	7	-0.042	-0.032	-0.004	-0.049	-0.035	-0.020	-0.051	-0.035	-0.013
3/20/91	13	-0.030	-0.551	-3.310	-2.420	-2.310	-0.070	-0.190	-2.020	-1.700
3/28/91	21	-1.337	-1.243	-4.518	-3.852	-3.910	-1.047	-0.901	-2.883	-2.481
4/5/91	29	-2.121	-3.845	-6.062	-2.303	-3.678	-2.048	-2.164	-1.578	-1.263
4/11/91	35	-3.472	-7.108	-5.605	-4.875	-3.696	-2.471	-2.541	-2.276	-1.713
4/18/91	42	-0.739	-2.616	-5.259	-4.309	-3.487	-2.035	-3.255	-2.664	-2.007
4/25/91	49	-1.387	-4.671	-4.689	-3.724	-2.892	-2.452	-3.332	-2.692	-1.841
5/2/91	56	-2.054	-5.826	-4.091	-6.266	-2.829	-2.800	-3.780	-2.534	-1.885
5/10/91	64	-5.385	-7.057	-3.734	-2.564	-2.774	-4.756	-4.216	-2.406	-1.970
5/16/91	70	-4.573	-5.497	-4.280	-2.671	-2.560	-4.566	-4.452	-2.731	-2.041
5/24/91	78	-3.894	-4.512	-3.818	-1.508	-2.082	-4.368	-4.375	-2.260	-2.073
5/30/91	84	-4.324	-5.027	-2.317	-2.049	-2.159	-4.477	-4.168	-2.283	-1.869
6/6/91	91	-4.120	-5.187	-2.206	-1.638	-2.808	-4.356	-4.172	-2.230	-1.200
6/13/91	98	System down (7AM - 4 PM). Measurements Taken After Startup.								
6/13/91	98	-0.115	-0.931	-0.458	0.322	0.187	-1.533	-4.191	0.216	-0.597
6/27/91	112	-0.232	-0.810	-0.396	0.416	0.123	-1.720	-3.862	-0.059	-0.608
7/18/91	133	-4.588	-3.740	-3.260	-2.807	-2.453	-3.225	-3.002	-2.040	-1.600
8/6/91	152	-3.960	-3.565	-3.339	-2.963	-2.803	-3.678	-2.609	-2.160	-1.383
8/23/91	169	-4.254	-5.377	-3.891	-3.200	-3.394	-3.132	-2.251	-2.916	-1.630
8/30/91	178	-5.840	-5.667	-2.778	-2.734	-2.811	-3.638	-4.108	-2.734	-2.139
9/5/91	184	-5.320	-4.870	-4.735	-3.460	-3.393	-3.409	-4.040	-3.665	-2.720
9/12/91	191	-5.268	-4.763	-4.744	-3.504	-3.169	-3.475	-3.734	-3.050	-1.887
9/26/91	205	-3.037	-4.028	-2.104	-2.510	-4.144	-4.034	-6.278	-2.891	-2.577
10/3/91	212	-3.836	-3.89	-2.532	-2.58	-3.872	-3.291	-5.229	-2.869	-2.109
10/11/91	220	-4.430	-3.627	-2.941	-2.614	-3.386	-2.948	-4.310	-2.886	-1.993
10/15/91	224	-4.111	-3.237	-2.682	-2.714	-3.506	-2.898	-4.198	-2.855	-1.880
10/24/91	233	-3.461	-3.297	-2.209	-2.218	-2.772	-2.69	-3.832	-2.13	-1.744
10/28/91	237	-3.172	-3.425	-1.206	-1.815	-2.521	-2.648	-2.798	-1.734	-1.870
11/07/91	247	-3.125	-3.32	-2.179	-1.19	-2.497	-4.233	-3.29	-1.835	-1.617
11/14/91	254	-2.987	-3.123	-2.14	-1.877	-2.511	-2.232	-2.633	-1.839	-1.685
11/25/91	265	-3.091	-3.045	-2.283	-1.687	-2.192	-2.566	-3.19	-1.67	-1.531
11/30/91	270	System Down 11/30/91 (12:05 AM) - 12/03/91 (2:10 PM).								
12/05/91	268	-3.144	-2.331	-2.331	-1.689	-2.219	-2.61	-3.284	-1.683	-1.559
12/12/91	275	-2.37	-2.61	-1.71	-1.48	-1.79	-2.24	-2.85	-1.72	-1.45
12/19/91	282	-2.11	-2.43	-1.68	-1.35	-1.73	-1.76	-2.57	-1.7	-1.36
12/26/91	289	-2.48	-2.73	-1.89	-1.67	-1.93	-2.36	-2.93	-1.75	-1.57
1/2/92	296	-1.87	-1.29	-1.22	-1.03	-1.38	-1.74	-2.01	-1.09	-1.36
1/9/92	303	-2.42	-2.6	-1.69	-1.53	-1.71	-2.33	-2.72	-1.75	-1.36
1/16/92	310	-2.13	-1.72	-1.46	-1.27	-1.65	-2.17	-3.05	-1.28	-1.52
1/23/92	317	-2.11	-1.82	-1.51	-1.32	-1.67	-2.04	-2.31	-1.63	-1.4
1/30/92	324	-1.93	-1.41	-1.36	-0.99	-1.55	-1.83	-2.25	-1.2	-1.38
2/6/92	331	-2.231	-1.347	-1.19	-1.199	-1.588	-2.123	-2.573	-1.076	-1.369
2/13/92	338	-2.288	-1.392	-1.297	-1.215	-1.59	-2.039	-2.442	-1.086	-1.411
2/20/92	345	-2.297	-1.389	-1.316	-1.214	-1.593	-1.886	-2.367	-1.084	-1.514
2/26/92	351	-2.681	-1.894	-1.865	-1.633	-2.177	-2.316	-2.713	-1.577	-1.958

mA Test Pipe Designation							
12	13	14	15	16	17	18	19
-0.034	-0.003	-0.026	-0.015	-0.048	-0.036	-0.021	-0.039
-0.009	-0.029	-0.058	-0.020	-0.021	-0.014	-0.048	-0.033
-0.011	-0.033	-0.057	-0.027	-0.017	-0.012	-0.015	-0.025
-0.047	-0.028	-0.005	-0.006	-0.014	-0.017	-0.051	-0.032
-0.037	-0.020	-1.310	-0.640	-0.015	-0.061	-0.060	-0.370
-1.187	-0.943	-3.188	-1.139	-0.914	-1.327	-2.357	-6.473
-1.188	-1.212	-1.652	-0.802	-0.756	-0.981	-4.323	-5.725
-1.438	-1.257	-2.034	-1.022	-0.985	-0.748	-4.903	-4.478
-1.566	-1.705	-2.467	-1.168	-1.150	-1.023	-5.214	-4.878
-1.794	-1.341	-2.387	-1.215	-1.109	-0.865	-5.226	-4.334
-1.922	-1.482	-2.011	-1.544	-1.237	-0.889	-5.193	-4.305
-2.334	-1.629	-1.887	-1.701	-1.472	-0.964	-5.083	-4.213
-2.334	-1.558	-2.302	-0.836	-1.541	-0.962	-4.758	-3.646
-2.270	-1.450	-1.905	-1.150	-1.490	-0.830	-4.640	-2.579
-2.189	-0.784	-2.107	-2.578	-1.832	-0.901	-4.732	-2.809
-2.038	-1.685	-2.019	-0.627	-1.744	-0.932	-4.294	-2.211
System down (7AM - 4 PM). Measurements Taken After Startup.							
-0.389	-1.731	-0.376	-0.225	-0.642	-0.787	-1.263	-0.381
-0.211	-1.503	-0.385	-0.264	-0.630	-0.672	-1.289	-0.356
-1.528	-1.548	-2.063	-1.680	-1.609	-0.802	-4.111	-2.830
-2.828	-1.730	-1.939	-1.814	-2.744	-0.872	-1.080	-2.454
-2.730	-1.509	-2.517	-1.892	-2.420	-1.080	-2.381	-2.435
-3.874	-2.153	-2.407	-2.168	-0.682	-1.417	-7.172	-3.728
-3.628	-1.874	-2.540	-2.206	-1.026	-1.370	-6.274	-4.302
-3.908	-1.774	-2.377	-2.106	-1.385	-1.411	-5.837	-3.312
-3.872	-3.041	-1.923	-1.452	-2.730	-1.678	-12.172	-3.935
-3.018	-2.963	-2.006	-1.867	-2.514	-1.677	-7.404	-3.248
-2.760	-2.633	-2.117	-3.007	-2.266	-1.610	-5.577	-2.638
-2.879	-2.070	-2.267	-2.939	-2.809	-1.650	-6.940	-2.831
-2.411	-2.155	-1.458	-2.382	-1.916	-1.438	-3.864	-2.025
-2.105	-2.470	-1.508	-1.891	-1.458	-1.560	-3.890	-2.397
-2.054	-2.218	-1.469	-1.588	-1.257	-1.324	-3.488	-1.874
-1.77	-1.96	-1.493	-1.53	-1.175	-1.164	-3.382	-1.664
-1.988	-2.023	-1.659	-1.425	-1.374	-1.186	-3.244	-1.757
System Down 11/30/91 (12:05 AM) - 12/03/91 (2:10 PM).							
-1.998	-2.054	-1.684	-1.453	-1.364	-1.184	-3.299	-1.796
-1.78	-1.91	-1.5	-1.36	-1.08	-1.19	-2.22	-1.44
-1.55	-1.72	-1.23	-1.02	-1.05	-1.17	-1.91	-1.38
-1.86	-2.03	-1.2	-1.38	-1.2	-1.22	-2.37	-1.56
-1.32	-1.18	-0.71	-0.98	-0.9	-0.92	-2.11	-1.2
-1.69	-1.9	-1.48	-1.32	-1.04	-1.16	-2.27	-1.3
-1.82	-2.03	-1.19	-1.18	-1.21	-1.02	-2.68	-1.7
-1.56	-1.72	-1.03	-0.95	-0.97	-1.02	-2.38	-1.16
-1.49	-1.2	-0.55	-0.94	-0.87	-0.87	-2.4	-1.27
-1.828	-1.268	-0.928	-0.887	-0.982	-0.731	-2.335	-2.06
-1.737	-1.234	-0.856	-0.954	-1.003	-0.849	-2.324	-1.878
-1.662	-1.235	-0.781	-1.018	-1.005	-0.924	-2.368	-1.393
-2.59	-1.724	-1.294	-1.295	-1.312	-1.191	-2.855	-2.045

Table 3. Potential profiles encountered on inside of pipes.

July 8,1991	mV Test Pipe Designation																	
	1		2		3		4		5		6		7		8		9	
ft*	in	out	in	out	in	out	in	out	in	out	in	out	in	out	in	out	in	out
0	137	125	156		94		78	74	59	61	125	116	118	112	154	140	109	
1	137	124	158		109		77	75	87	83	126	112	117	107	152	134	127	
2	132	120	157		95		75	74	76	71	122	112	118	105	146	129	113	
3	127	116	154		80		74	70	74	73	124	108	116	103	139	120	103	
4	121	111	150		73		71	66	71	63	130	113	112	99	131	118	99	
5	115	105	142		62		69	64	60	61	135	116	105	93	125	112	94	
6	106	96	131		60		66	59	63	62	136	113	99	85	119	104	87	
7	96	84	117		46		63	61	60	56	124	106	88	77	111	96	80	
8	78	66	96		20		51	50	46	42	109	93	75	68	98	88	70	
9	53	38	66		-10		22	19	30	30	90	74	59	51	80	71	50	
10	22	0	19		-57		-18	-19	6	-4	58	46	26	20	48	44	16	
11	-30	-61	-55		-136		-70	-83	-22	-46	5	-8	-14	-27	-9	-19	-31	
12	-96	-115	-104		-172		-129	-134	-90	-85	-46	-69	-65	-88	-70	-88	-92	
13	-116	-134	-104		-145		-150	-153	-120	-114	-89	-102	-101	-102	-100	-98	-103	
14	-126	-141	-102		-130		-163	-164	-124	-122	-110	-120	-110	-111	-106	-99	-101	
15	-130	-141	-99		-125		-172	-174	-120	-120	-114	-121	-108	-113	-109	-102	-103	
16	-130	-140	-96		-172		-179	-180	-116	-118	-108	-115	-106	-110	-109	-98	-107	
17	-126	-135	-98		-159		-187	-188	-116	-118	-99	-107	-106	-108	-108	-99	-110	
18	-125	-133	-102		-149		-192	-192	-118	-118	-98	-104	-108	-108	-104	-96	-107	
19	-126	-131	-101		-149		-197	-199			-102	-109			-103	-99	-108	
20	-125	-130	-102		-148		-200	-200			-113	-115			-104	-103	-116	
21	-130	-132	-113		-148		-201	-201			-122	-124			-105	-105	-118	
22			-126		-150		-200	-201			-130	-130			-109	-109	-121	
23																		
24																		
25																		
26																		
27																		
28																		
29																		
30																		
32																		

July 8,1991										mV Test Pipe Designation									
10		11		12		13		14		15		16		17		18		19	
in	out	in	out	in	out	in	out	in	out	in	out	in	out	in	out	in	out	in	out
77	67	158	139	104	84	141		216	180	156	173	177	168	120	107	105	94	156	146
76	66	157	141	105	83	136		211	165	160	172	174	164	123	106	120	101	151	144
73	67	156	140	96	74	131		208	175	155	170	160	156	120	105	115	82	146	138
81	70	155	140	85	64	124		206	191	162	170	162	156	120	106	85	75	139	132
91	74	154	143	75	57	119		202	162	161	167	164	154	106	107	75	65	132	128
104	80	153	140	71	48	113		197	164	157	165	155	152	96	104	75	71	125	122
108	79	150	138	60	39	106		190	167	150	165	132	153	97	102	84	78	115	113
106	73	140	128	50	30	98		180	165	142	157	109	152	91	98	84	80	103	102
97	63	126	114	40	18	88		169	160	128	141	85	138	96	93	85	81	88	86
80	43	105	96	27	6	70		145	150	108	118	65	91	90	87	70	72	66	64
58	14	81	69	10	-9	47		116	130	82	88	32	34	83	79	47	49	31	28
23	-32	38	27	-8	-31	11		76	101	48	52	6	-20	75	64	10	7	-20	-29
-2	-47	-6	-19	-23	-53	-35		52	62	40	45	14	-20	63	44	-10	-10	-70	-75
-24	-63	-54	-73	-48	-80	-81		44	46	32	38	9	-17	50	26				
-71	-100	-98	-117	-85	-119	-120		40	38	21	22	-5	-30	30	3				
-80	-102	-122	-128	-102	-142	-108		28	28	14	14	-9	-23	8	-10				
-82	-105	-124	-131	-107	-160	-109		5	16	3	0	-9	-19	-14	-36				
-92	-103	-113	-129	-117	-195	-109		-13	-4	-4	-9	-8	-18	-42	-58				
-114	-114	-103	-131	-160	-216	-109		-26	-20	-13	-7	-12	-23	-64	-80				
		-95	-114	-191	-230	-111		-39	-32	-26	-20	-25	-36	-83	-101				
		-86	-102	-179	-220	-116		-53	-35	-43	-33	-50	-58	-102	-125				
		-89	-100	-163	-213	-118		-45	-54	-76	-54	-75	-87	-120	-146				
		-105	-111	-166	-215	-116		-86	-85	-92	-86	-88	-98	-122	-130				
		-115	-118	-168	-218	-112		-113	-114	-93	-94	-92	-102	-115	-123				
		-124	-125	-171	-218	-122		-118	-124	-103	-97	-94	-102	-124	-132				
				-173	-220	-126		-118	-124	-107	-106	-94	-103	-130	-143				
								-113	-124	-110	-106	-91	-102	-140	-144				
								-110	-120	-111	-112	-89	-104	-141	-144				
								-104	-116	-110	-113	-83	-105	-142	-145				
								-103	-116	-112	-113	-78	-105	-145	-148				
								-106	-134	-112	-113	-82	-101	-150	-152				
								-118	-128	-115	-115	-100	-103	-153	-154				

August 6,1991																		
	mV Test Pipe Designation																	
	1		2		3		4		5		6		7		8		9	
ft*	in	out	in	out	in	out	in	out	in	out	in	out	in	out	in	out	in	out
0	165	135	157		225	207	225	206	187		216	191	141	190	207		105	87
1	163	138	160		220	196	228	188	189		218	195	166	210	205		101	82
2	158	130	162		212	202	219	187	192		216	196	163	205	202		90	74
3	154	125	162		205	208	209	181	184		212	194	166	200	200		88	73
4	148	121	157		209	206	204	179	177		209	189	166	191	197		83	75
5	140	114	147		207	209	194	173	170		204	182	162	176	199		77	73
6	132	114	140		206	207	186	166	160		188	172	153	160	196		75	68
7	118	105	130		197	204	177	160	146		170	153	138	140	182		69	65
8	95	91	106		185	194	163	149	130		149	127	119	112	154		60	59
9	79	71	83		169	180	143	130	108		122	94	87	74	93		42	43
10	27	39	51		148	159	109	97	74		80	48	29	15	15		12	17
11	-36	-84	2		89	112	47	24	10		15	-27	18	5	-61		-29	-28
12	-76	-109	-63		45	63	-7	-21	-60		-49	-105	-80	-53	-81		-80	-80
13	-96	-108	-80		24	35	-23	-26	-70		-89	-117	-107	-110	-86		-101	-104
14	-97	-107	-89		-1	9	-26	-28	-60		-100	-116	-114	-120	-104		-105	-112
15	-91	-100	-91		-31	-17	-30	-32	-48		-99	-102	-132	-130	-103		-107	-117
16	-84	-85	-94		-24	-19	-33	-36	-50		-94	-84	-129	-132	-103		-110	-118
17			-94		-19	-15	-36	-40	-43						-103		-115	-119
18			-92		-11	-7	-36	-39							-105		-112	-117
19			-90		-4	-1	-32	-37							-103		-113	-116
20			-96		-5	-4	-29	-35							-100		-114	-117
21			-89		-3	-7	-27	-33									-119	-120
22			-98		-2	-7	-28	-29									-123	-122
23			-103															
24																		
25																		
26																		
27																		
28																		
29																		
30																		
32																		

August 6,1991												mV Test Pipe Designation							
10		11		12		13		14		15		16		17		18		19	
in	out	in	out	in	out	in	out	in	out	in	out	in	out	in	out	in	out	in	out
127	118	160		174	135	60	110	269		234	257	271	228	240	241	230	150	225	178
121	145	163		173	139	91	114	272		243	257	272	211	242	232	231	152	218	174
129	153	156		162	136	103	116	267		241	252	270	212	238	221	228	149	215	188
142	157	156		163	132	114	125	263		235	248	267	210	234	217	219	156	211	193
152	161	158		160	132	118	129	252		231	243	233	209	226	215	214	158	206	192
155	163	155		155	130	122	134	246		224	236	211	191	220	206	208	157	202	190
156	156	150		150	127	131	129	233		215	226	181	163	213	197	204	151	184	181
145	138	139		141	119	128	128	215		201	213	147	94	207	194	199	149	170	169
130	119	124		130	108	127	122	188		182	194	111	58	199	183	186	142	154	154
102	85	106		107	89	120	113	152		155	166	76	13	188	174	162	136	123	124
64	40	82		82	62	108	97	99		120	135	41	-32	175	162	125	115	75	75
-18	-22	47		42	15	92	82	72		88	105	-6	-39	152	141	67	95	8	6
-5	-18	2		30	12	68	44	72		77	88	-3	-34	133	122	49			
-15	-22	-40		-1	-15	44	5	65		66	73	-9	-5	110	96	6			
-67	-48	-86		-45	-66	13	-20	59		56	55	-27	-2	83	70	-44			
-82	-96	-104		-64	-83	-20	-37	46		44	40	-52	-22	59	49				
-91	-118	-104		-66	-95	-39	-55	35		36	23	-63	-31	37	27				
-105	-120			-73	-121	-59	-71	16		3	7	-71	-37	12	3				
				-95	-124	-71	-79			5	5	-66	-37	-8	-18				
				-92	-121	-80	-86			3	-7	-49	-24	-31	-37				
				-89	-126	-86	-92			4	-9	-10	-17	-50	-58				
				-94	-131	-90	-95					-33	-69	-71	-86				
				-95	-130	-92	-97					-44	-81	-95	-116				
				-93	-133	-92	-96					-47	-81	-118	-133				
				-109	-115	-93	-96					-48	-85	-85	-93				
												-55	-86	-51	-59				
												-57	-85	-31	-42				
												-59	-85	-20	-28				
												-59	-85	-18	-20				
												-52	-82						
												-60	-74						
												-69	-72						

August 26,1991	mV Test Pipe Designation																	
	1		2		3		4		5		6		7		8		9	
ft*	in	out	in	out	in	out	in	out	in	out	in	out	in	out	in	out	in	out
0	149	154	214	236	166	164	160	160	195	196	135	146	223	220	173	164	103	94
1	162	160	210	230	164	158	152	154	192	198	127	150	218	216	171	163	100	88
2	163	163	200	226	159	154	142	142	186	193	125	147	220	212	162	157	93	94
3	153	109	186	206	160	154	135	134	193	196	115	145	220	207	161	156	90	89
4	140	97	184	200	151	150	126	123	180	189	110	134	219	209	158	153	89	91
5	110	90	196	195	140	140	115	118	186	180	99	140	209	196	154	148	86	76
6	110	89	238	180	128	127	106	108	175	178	90	130	198	189	150	143	84	72
7	85	75	190	159	110	96	96	100	150	160	97	106	190	178	142	135	76	62
8	76	64	143	151	107	87	83	83	153	122	81	90	172	162	122	115	66	40
9	42	46	121	120	85	76	59	60	132	103	69	68	154	154	87	75	40	36
10	19	18	85	90	40	36	23	17	85	79	24	13	130	120	32	20	11	0
11	6	8	70	74	-33	-54	-36	-50	64	83	-10	-6	96	84	-16	-36	-10	-30
12	-40	-30	68	65	-82	-78	-73	-74	53	78	-16	-76	80	63	-77	-90	-20	-30
13	-3	-28	65	68	-92	-11	-75	-76	61	40	-12	-64	67	49	-88	-94	-16	-49
14	45	-34	63	60	-116	-105	-79	-77	60	27	-6	-73	71	69	-91	-96	-20	-10
15	48	-30	80	80	-98	-90	-79	-78	62	26	-14	-24	72	72	-92	-95	-22	-34
16	48	-24	88	90	-96	-65	-80	-77	66	38	-20	-10	89	76	-95	-95	-19	-28
17	-18	-30	102	66	-92	-64	-74	-74	74	40	-12	-18	82	80	-93	-93	-15	-26
18	-23	-19	123	44	-77	-71	-75	-64	70	42	-19	-34	99	84	-93	-92	-16	-30
19	15	-8	194	28	-66	-65	-70	-59	96	62	9	9	93	90	-91	-92	10	-15
20	18	-3	70	23	-54	-54	-67	-66	67	52			92	95	-93	-93	34	-4
21			55	26			-36	-40	48	46			110	105	-92	-93	40	12
22							-38	-40							-91	-93		
23																		
24																		
25																		
26																		
27																		
28																		
29																		
30																		

August 26,1991

mV

Test Pipe Designation

10		11		12		13		14		15		16		17		18		19	
in	out	in	out	in	out	in	out	in	out	in	out	in	out	in	out	in	out	in	out
120	125	134	130	166	152	180	168	246	256	232	225	198	186	194	204	200	188	164	156
132	138	122	122	156	149	169	159	242	248	225	227	190	184	185	214	194	186	162	154
127	126	119	120	144	140	164	163	230	237	219	229	178	170	175	210	186	176	156	149
134	132	126	124	140	136	162	153	231	240	218	228	185	176	178	202	183	172	149	144
136	129	130	132	139	128	157	160	228	232	214	218	190	180	176	196	179	168	141	140
123	130	140	135	140	134	166	155	229	236	212	198.	185	174	181	196	176	163	133	132
112	137	133	131	138	124	153	148	225	230	209	190	176	170	182	190	166	156	122	123
111	117	128	124	124	113	146	144	220	234	202	178	162	158	179	187	154	141	112	111
103	104	119	112	119	108	134	136	208	218	192	180	153	152	169	174	134	116	96	93
61	70	102	93	91	92	119	120	187	190	172	176	144	140	160	170	100	83	70	66
70	64	85	69	69	74	100	106	157	167	144	154	135	129	152	160	44	24	32	30
72	49	58	28	65	62	84	85	156	157	136	138	122	125	141	146	-90	-80	-30	-30
46	44	28	-16	50	54	71	64	158	157	128	120	115	121	134	140				
20	41	7	-45	-20	-30	54	52	164	150	115	111	114	119	114	119				
22	26	-11	-58	-11	-20	41	41	162	148	110	109	111	113	100	107				
30	-3	-17	-54	-20	-24	36	36	147	136	103	96	112	112	84	103				
10	23	-23	-61	-22	-19	44	29	119	115	103	98	113	105	80	97				
6	-15	-3	-48	-13	-14	31	29	111	104	113	95	94	90	63	90				
33	-3	4	-32	-16	-12	40	36	104	110	108	90	93	88	58	86				
6	9	24	-8	-38	-26	54	42	97	98	106	85	88	76	47	78				
8	-23	44	4	-40	-50	64	61	85	90	90	80	62	60	31	69				
-6	-86	5	30	-49	-34	74	69	80	94	61	62	59	55	20	68				
-14	-32	12	-3	-30	-13	66	59	85	100	70	65	57	45	17	53				
-110	-63	18	10	-38	-20	60	54	98	108	81	81	54	50	36	70				
								95	113	86	88	74	64	70	66				
								115	111	79	70	66	62	76	61				
								110	106	84	73	64	64	52	64				
								113	120	85	78	72	62	84	76				
								119	101	84	80	55	58	90	78				
								109	100	73	16	66	69	101	100				
								96	98	78	18	79	74	104	103				

September 5, 1991	mV Test Pipe Designation																	
	1		2		3		4		5		6		7		8		9	
ft*	**in**	**out**	**in**	**out**	**in**	**out**	**in**	**out**	**in**	**out**	**in**	**out**	**in**	**out**	**in**	**out**	**in**	**out**
0	168	164	174	168	168	166	168	163	146	131	214	214	212	210	160	157	170	154
1	166	159	171	167	164	158	162	157	141	129	208	206	210	207	155	153	163	147
2	159	154	169	168	164	158	156	152	139	129	208	205	205	204	154	152	160	148
3	153	144	170	167	163	156	150	147	135	129	207	205	199	195	151	149	158	149
4	144	135	166	163	160	153	145	141	132	125	202	199	187	182	149	145	156	147
5	132	124	160	156	154	148	139	133	124	121	188	189	171	166	145	141	153	145
6	116	109	151	147	146	140	131	126	110	112	170	170	151	144	136	133	146	140
7	97	90	138	123	133	123	118	112	94	99	143	144	127	121	117	118	133	129
8	73	62	113	103	109	101	89	87	61	78	108	113	96	88	90	90	110	104
9	37	24	65	55	71	70	49	47	20	26	56	62	49	39	35	-39	65	57
10	-38	-42	-45	-25	-8	-5	-25	-35	-70	-48	-20	-10	-24	-32	-30	-44	-14	-21
11	-86	-82	-85	-92	-80	-100	-85	-104	-135	-136	-116	-120	-97	-105	-80	-107	-85	-109
12	-105	-107	-93	-98	-101	-115	-85	-107	-144	-151	-152	-151	-103	-112	-95	-110	-95	-123
13	-117	-123	-94	-97	-121	-133	-89	-111	-146	-152	-158	-159	-103	-111	-96	-107	-92	-118
14	-122	-134	-97	-100	-110	-121	-86	-112	-141	-147	-159	-162	-106	-110	-97	-104	-90	-111
15	-122	-143	-98	-102	-110	-121	-87	-110	-132	-140	-157	-160	-107	-111	-99	-104	-90	-105
16	-120	-141	-100	-103	-104	-110	-88	-106	-132	-137	-153	-156	-106	-108	-99	-106	-93	-103
17	-117	-141	-104	-106	-97	-100	-87	-98	-136	-141	-150	-152	-107	-109	-99	-104	-98	-104
18	-116	-140	-107	-113	-99	-103	-85	-97	-137	-144	-152	-153	-109	-110	-100	-103	-99	-104
19	-116	-134	-112	-124	-111	-114	-83	-97	-146	-150	-153	-154	-116	-117	-103	-104	-101	-108
20	-116	-121	-112	-125	-126	-126	-86	-97	-144	-149	-151	-152	-121	-122	-105	-99	-102	-113
21			-113	-114	-130	-131	-90	-96	-140	-145	-150	-150	-124	-124	-100	-100	-107	-112
22																		
23																		
24																		
25																		
26																		
27																		
28																		
29																		
30																		

September 5, 1991										mV Test Pipe Designation									
10		11		12		13		14		15		16		17		18		19	
in	out	in	out	in	out	in	out	in	out	in	out	in	out	in	out	in	out	in	out
179	166	184	157	162	161	173	167	230	231	266	248	52	46	190	184	181	178	191	191
185	125	181	168	163	161	163	159	232	232	264	252	47	42	187	180	176	173	179	177
192	188	182	171	165	163	157	156	233	231	262	255	43	38	184	177	171	169	162	163
193	189	184	174	167	163	153	154	232	232	258	251	39	34	180	172	164	164	146	151
189	184	182	172	168	163	148	149	229	230	252	245	34	29	175	167	159	158	130	136
180	172	176	168	166	160	141	142	224	225	244	238	29	24	167	161	152	150	113	119
167	157	164	157	159	153	131	130	214	215	233	227	24	19	159	153	141	139	94	97
149	139	149	142	148	145	119	120	199	201	218	210	19	15	150	145	122	123	69	70
123	109	124	120	128	127	101	102	174	176	198	186	14	8	140	135	94	95	36	41
80	70	98	91	84	90	78	74	129	132	163	151	7	4	125	120	35	37	-19	-19
24	10	50	38	16	9	36	44	81	82	127	108	-4	-4	94	94	-60	-62	-111	-95
10	-18	-10	-24	7	-13	-5	-8	66	65	115	95	-13	-13	74	64				
-18	-40	-64	-77	-29	-47	-47	-54	55	51	102	78	-17	-18	52	42				
-92	-109	-112	-127	-110	-122	-86	-95	47	39	84	62	-20	-20	30	18				
-98	-124	-109	-123	-122	-132	-94	-100	30	22	68	47	-33	-31	6	-4				
-105	-126	-110	-123	-124	-136	-106	-107	15	10	52	31	-50	-49	-15	-27				
-116	-132	-111	-126	-140	-155	-109	-113	-3	-3	37	16	-65	-66	-34	-48				
-128	-134	-111	-126	-145	-152	-108	-111	-19	-18	20	-2	-83	-84	-60	-69				
-136	-140	-106	-123	-158	-166	-105	-109	-36	-37	1	-28	-100	-103	-82	-90				
-142	-145	-102	-125	-154	-165	-104	-107	-73	-68	-30	-55	-119	-121	-104	-115				
-146	-149	-111	-128	-149	-160	-102	-106	-118	-122	-68	-93	-140	-140	-126	-136				
-147	-149	-121	-134	-151	-153	-101	-105	-124	-131	-79	-85	-155	-154	-155	-160				
-146	-148	-128	-136	-170	-172	-101	-103	-122	-132	-80	-89	-166	-167	-157	-171				
-146	-146	-133	-139	-161	-161	-105	-106	-114	-123	-89	-100	-177	-177	-148	-163				
								-105	-111	-102	-116	-184	-184	-141	-150				
								-101	-106	-110	-120	-189	-190	-141	-147				
								-96	-99	-116	-124	-194	-193	-141	-146				
								-82	-96	-119	-128	-196	-196	-139	-144				
								-101	-110	-116	-126	-198	-198	-135	-138				
								-104	-109	-113	-121	-200	-199	-130	-132				
								-106	-106	-113	-114	-201	-201	-130	-130				

September 16, 1991	mV Test Pipe Designation																	
	1		2		3		4		5		6		7		8		9	
ft*	in	out	in	out	in	out	in	out	in	out	in	out	in	out	in	out	in	out
0	167	156	189	180	181	171	178	166	159	135	228	209	220	215	166	158	162	147
1	159	150	187	177	177	169	174	161	129	140	227	206	210	213	164	158	155	146
2	143	147	184	178	176	169	170	162	116	141	225	213	198	212	161	156	151	148
3	146	146	179	174	175	168	166	159	119	138	221	216	192	204	158	154	149	145
4	141	139	173	169	173	165	160	156	129	133	217	210	184	190	155	151	146	142
5	131	128	164	160	169	159	155	152	130	127	208	200	166	171	152	147	143	137
6	114	111	153	149	161	152	150	146	124	117	191	183	143	146	145	139	137	131
7	95	93	138	134	150	140	140	137	121	103	169	160	118	120	129	123	126	119
8	70	65	114	113	132	120	119	116	99	89	136	128	83	86	104	97	105	96
9	29	22	59	55	95	79	78	76	65	48	89	81	31	34	58	45	66	52
10	-34	-46	-26	-36	36	5	-2	-3	4	25	14	6	-37	-34	-9	-29	0	-22
11	-84	-97	-78	-85	-66	-106	-71	-83	-71	-96	-63	-86	-105	-103	-74	-102	-73	-112
12	-101	-116	-84	-87	-75	-92	-79	-88	-92	-101	-97	-111	-118	-123	-90	-102	-86	-107
13	-111	-125	-79	-85	-76	-91	-81	-94	-93	-107	-100	-113	-125	-132	-94	-101	-81	-106
14	-116	-131	-80	-85	-74	-94	-83	-98	-86	-106	-96	-109	-132	-140	-98	-102	-78	-103
15	-116	-132	-80	-84	-76	-110	-87	-99	-82	-102	-86	-98	-129	-138	-100	-104	-79	-99
16	-115	-133	-77	-82	-83	-97	-91	-101	-84	-106	-73	-87	-103	-118	-102	-107	-84	-94
17	-115	-126	-77	-81	-87	-85	-91	-106	-90	-102	-65	-79	-91	-102	-101	-106	-91	-96
18	-115	-123	-80	-85	-87	-85	-91	-114	-90	-100	-68	-75	-92	-102	-102	-106	-92	-94
19	-115	-121	-84	-86	-89	-88	-89	-127	-91	-98	-76	-86	-104	-116	-103	-107	-94	-97
20	-116	-116	-88	-91	-87	-92	-92	-132	-93	-94	-89	-92	-116	-121	-104	-106	-95	-97
21			-87	-87	-88	-87	-99	-114			-94	-92	-120	-119	-103	-104	-97	-100
22																		
23																		
24																		
25																		
26																		
27																		
28																		
29																		
30																		

September 16, 1991												mV Test Pipe Designation							
10		11		12		13		14		15		16		17		18		19	
in	out	in	out	in	out	in	out	in	out	in	out	in	out	in	out	in	out	in	out
173	157	200	178	167	152	175	158	254	180	261	247	172	165	202	198	178	175	204	198
185	172	178	178	165	153	170	156	245	176	259	250	171	162	200	194	173	171	184	180
195	183	158	180	165	155	168	152	238	180	258	252	169	159	197	194	168	166	166	169
198	188	162	180	166	156	166	148	240	196	256	251	166	156	192	192	163	162	150	154
192	184	170	177	166	156	163	148	237	205	252	247	152	143	187	198	156	155	133	138
180	172	173	172	164	155	158	145	235	204	246	241	132	120	180	179	150	149	116	120
161	151	167	160	158	149	152	138	227	195	236	233	109	97	174	172	139	138	94	98
126	124	156	146	150	141	144	126	213	181	222	218	87	75	166	164	123	122	71	73
104	89	138	127	133	124	132	102	191	159	198	195	67	52	157	155	95	95	38	41
59	37	108	96	90	84	108	63	149	109	161	155	43	26	143	141	31	26	-9	-10
6	-22	67	50	24	-12	69	8	103	52	121	114	17	-2	117	116	-71	-85	-87	-87
0	-29	20	-1	11	-3	19	-48	93	35	108	102	12	0	96	94				
-15	-34	-27	-54	-24	-37	-31	-102	90	31	96	86	6	-2	75	71				
-62	-84	-68	-100	-90	-108	-77	-107	87	31	83	72	-8	-14	58	52				
-77	-105	-87	-112	-104	-119	-88	-103	74	19	71	57	-18	-22	38	30				
-76	-109	-100	-118	-112	-128	-94	-105	57	1	56	43	-20	-23	19	12				
-82	-109	-106	-122	-123	-148	-103	-105	44	-13	44	29	-16	-19	1	-6				
-99	-116	-116	-126	-135	-154	-103	-103	30	-29	28	12	-18	-22	-21	-26				
-112	-125	-107	-115	-141	-161	-100	-100	12	-44	9	-4	-27	-35	-41	-45				
-123	-133	-97	-105	-149	-168	-94	-101	-16	-76	-22	-35	-52	-65	-61	-67				
-127	-136	-96	-102	-132	-152	-90	-106	-69	-124	-64	-81	-90	-99	-80	-85				
-135	-137	-102	-110	-129	-146	-88	-110	-83	-136	-73	-85	-94	-95	-81	-96				
-134	-136	-109	-111	-126	-146	-90	-113	-85	-139	-72	-83	-95	-95	-66	-77				
-132	-134	-113	-113	-125	-126	-102	-114	-85	-134	-79	-95	-98	-99	-74	-79				
								-79	-135	-85	-101	-100	-100	-80	-78				
								-78	-128	-94	-109	-102	-101	-77	-77				
								-73	-120	-102	-109	-102	-102	-76	-80				
								-76	-124	-104	-112	-102	-102	-74	-81				
								-78	-133	-105	-110	-103	-102	-74	-81				
								-76	-132	-102	-110	-104	-104	-76	-78				
								-125	-124	-94	-94	-103	-103	-75	-76				

September 25, 1991									mV									
	Test Pipe Designation																	
	1		2		3		4		5		6		7		8		9	
ft*	in	out	in	out	in	out	in	out	in	out	in	out	in	out	in	out	in	out
0	118	107	100	100	135	133	169	164	-38	-42	83	77	119	114	145	141	182	180
1	114	108	76	78	119	117	163	160	-45	-50	70	71	109	109	141	139	184	182
2	111	105	53	56	101	99	157	153	-53	-52	59	59	97	100	139	137	185	185
3	105	99	32	34	84	80	151	147	-60	-59	48	47	92	96	138	136	186	187
4	97	92	10	11	64	61	144	141	-67	-66	34	33	89	93	138	135	187	188
5	85	81	-11	-10	46	43	136	133	-74	-72	21	21	84	90	136	131	187	188
6	65	61	-35	-34	26	23	128	124	-82	-76	8	7	78	86	131	128	186	187
7	40	35	-56	-55	6	4	116	113	-88	-84	-5	-6	73	84	116	116	183	184
8	8	1	-77	-76	-21	-25	89	88	-96	-91	-24	-23	66	79	92	93	177	178
9	-46	-54	-101	-99	-62	-67	37	40	-103	-100	-54	-54	33	45	48	48	157	159
10	-113	-122	-122	-121	-102	-110	34	-35	-112	-111	-91	-90	-54	-50	-15	-14	49	49
11	-135	-155	-134	-134	-141	-156	-95	-96	-143	-145	-131	-131	-152	-153	-85	-84	-83	-77
12	-136	-149	-132	-132	-154	-166	-115	-118	-150	-155	-150	-150	-171	-173	-115	-115	-115	-116
13	-132	-143	-129	-129	-157	-170	-124	-126	-142	-146	-152	-153	-174	-176	-120	-121	-115	-118
14	-126	-138	-127	-127	-156	-170	-130	-131	-136	-139	-150	-152	-178	-180	-116	-117	-102	-109
15	-126	-138	-124	-124	-158	-173	-133	-134	-132	-136	-147	-150	-177	-178	-110	-111	-89	-95
16	-132	-139	-120	-120	-160	-165	-134	-136	-135	-142	-145	-150	-172	-173	-106	-108	-82	-88
17	-140	-148	-113	-114	-157	-158	-136	-137	-134	-140	-149	-156	-167	-169	-103	-105	-85	-88
18	-150	-159	-106	-107	-154	-154	-138	-139	-135	-141	-153	-160	-168	-172	-106	-107	-84	-87
19	-160	-168	-102	-102	-151	-149	-134	-136	-141	-148	-160	-168	-176	-177	-114	-114	-89	-90
20	-169	-170	-107	-107	-145	-145	-135	-135	-154	-154	-170	-172	-183	-182	-122	-121	-98	-97
21											-176	-177	-185	-185	-122	-122	-100	-101
22																		
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September 25, 1991

mV

Test Pipe Designation

10		11		12		13		14		15		16		17		18		19	
in	out	in	out	in	out	in	out	in	out	in	out	in	out	in	out	in	out	in	out
177	164	207	198	187	184	196	190	162	142	222	208	209	207	200	196	219	220	174	170
176	176	204	207	190	189	197	194	161	142	218	218	207	206	195	195	221	222	166	167
190	187	200	210	194	194	196	199	157	137	219	222	207	206	193	192	225	226	156	160
205	197	206	211	199	200	200	200	151	140	219	222	205	204	190	188	227	226	144	147
203	197	208	211	203	204	205	198	144	135	218	222	194	193	187	185	228	225	129	134
193	188	206	208	206	206	208	200	130	122	212	216	172	171	182	180	228	225	115	118
172	168	197	199	209	206	210	203	109	102	200	202	150	149	176	174	226	226	96	100
139	134	184	185	209	207	210	205	88	82	175	177	127	127	170	169	223	225	76	78
96	92	163	164	207	205	208	204	66	62	146	148	104	104	162	162	219	222	49	51
38	33	125	127	188	187	186	183	35	36	113	116	72	72	148	150	193	196	5	8
-29	-32	58	60	114	116	127	125	2	3	83	88	28	27	124	126	21	22	-53	-53
-48	-51	-9	-7	47	47	52	50	-10	-12	62	65	10	7	103	104				
-80	-83	-81	-83	-21	-20	-25	-26	-23	-24	38	40	24	21	77	76				
-140	-172	-140	-142	-88	-87	-93	-91	-34	-35	17	19	53	50	53	52				
-140	-171	-147	-152	-126	-129	-127	-126	-46	-47	-5	-2	65	63	27	27				
-124	-126	-140	-146	-136	-142	-141	-141	-57	-58	-25	-24	70	68	3	3				
-105	-112	-121	-132	-133	-147	-151	-150	-69	-70	-46	-45	72	71	-22	-21				
-107	-114	-104	-116	-127	-145	-155	-153	-82	-82	-71	-70	66	66	-47	-46				
-117	-125	-91	-106	-134	-146	-158	-155	-95	-96	-99	-98	45	45	-71	-70				
-129	-137	-96	-109	-142	-150	-159	-156	-112	-115	-128	-128	-2	-2	-97	-96				
-140	-146	-128	-129	-150	-154	-156	-155	-135	-140	-149	-151	-55	-59	-121	-122				
-151	-154	-139	-140	-156	-159	-151	-152	-146	-151	-147	-150	-63	-68	-123	-127				
-161	-163	-146	-147	-156	-158	-147	-147	-155	-159	-145	-150	-63	-67	-101	-106				
-170	-170	-152	-152	-150	-151	-142	-142	-161	-165	-131	-137	-66	-69	-86	-95				
								-164	-167	-119	-126	-70	-73	-77	-82				
								-165	-166	-118	-123	-75	-78	-74	-82				
								-167	-168	-124	-127	-81	-83	-82	-88				
								-171	-173	-138	-139	-86	-88	-95	-99				
								-171	-173	-152	-153	-89	-91	-106	-109				
								-169	-172	-160	-160	-96	-96	-116	-118				
								-170	-170	-159	-159	-101	-101	-117	-117				

January 21, 1992	mV Test Pipe Designation																	
	1		2		3		4		5		6		7		8		9	
ft*	in	out	in	out	in	out	in	out	in	out	in	out	in	out	in	out	in	out
0	209	206	180	173	164	159	93	91	125	118	100	99	167	150	180	158	184	183
1	206	203	175	169	158	153	86	86	120	114	94	97	161	144	174	153	178	176
2	201	202	170	165	153	148	83	82	113	110	88	94	154	139	176	156	172	170
3	197	197	165	160	150	142	80	78	104	103	81	88	149	142	172	157	166	164
4	187	187	160	155	145	137	75	73	97	96	74	83	140	142	170	156	159	157
5	169	171	153	149	141	131	71	69	86	86	62	71	131	134	164	153	150	149
6	142	146	143	140	137	125	65	61	70	74	48	60	115	123	151	142	141	141
7	110	102	####	120	130	114	56	52	52	60	29	41	98	106	130	124	130	129
8	70	66	99	86	114	96	39	34	37	40	16	25	77	84	106	99	115	112
9	9	9	50	41	85	62	8	1	17	17	-1	-2	45	48	68	62	83	84
10	-38	-48	-5	-14	24	-9	-44	-52	-14	-13	-40	-40	-7	0	16	11	9	11
11	-74	-80	-47	-66	-40	-90	-85	-100	-55	-52	-88	-89	-53	-56	-38	-52	-62	-70
12	-83	-90	-67	-76	-59	-84	-91	-98	-67	-65	-104	-103	-55	-67	-69	-72	-83	-83
13	-83	-88	-69	-75	-60	-90	-91	-97	-52	-61	-103	-105	-50	-63	-78	-81	-91	-90
14	-81	-80	-71	-76	-58	-82	-86	-93	-36	-43	-100	-100	-49	-59	-83	-86	-95	-93
15	-79	-80	-71	-76	-57	-75	-83	-88	-30	-43	-86	-89	-42	-50	-86	-88	-99	-98
16	-75	-83	-73	-76	-61	-70	-80	-81	-32	-57	-62	-67	-39	-45	-88	-89	-103	-104
17	-70	-69	-74	-77	-64	-68	-76	-75	-42	-56	-49	-54	-38	-43	-87	-89	-106	-106
18	-68	-60	-75	-80	-69	-70	-75	-73	-42	-52	-50	-55	-43	-45	-86	-85	-105	-106
19	-68	-60	-77	-83	-72	-71	-72	-69	-40	-51	-56	-64	-51	-56	-86	-85	-99	-103
20	-75	-65	-82	-86	-73	-68	-73	-70	-43	-42	-69	-63	-55	-57	-86	-76	-100	-98
21							-75	-75							-75	-77	-94	-94
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January 21, 1992														mV Test Pipe Designation					
10		11		12		13		14		15		16		17		18		19	
in	out	in	out	in	out	in	out	in	out	in	out	in	out	in	out	in	out	in	out
110	111	249	230	166	156	180	178	47	32	229	227	169	158	227	222	238	230	200	198
107	110	217	230	162	154	171	170	41	29	233	231	164	161	225	223	234	228	192	178
105	108	224	240	160	153	169	169	36	25	237	235	167	163	225	226	231	229	177	168
100	105	230	239	156	150	169	167	32	21	239	237	169	132	226	226	224	223	159	152
90	97	231	235	151	146	169	165	28	16	239	237	165	156	226	224	214	215	139	132
79	88	227	229	146	142	167	163	22	12	237	235	157	146	224	222	202	204	117	113
65	72	219	217	140	136	163	159	15	8	232	229	146	134	223	218	188	190	94	90
42	54	206	201	133	129	158	154	9	2	221	215	136	122	215	211	171	174	70	68
25	29	188	175	124	119	151	145	0	-6	206	204	124	110	202	199	146	151	43	41
0	5	142	132	100	96	134	130	-14	-23	185	184	108	93	182	180	100	106	6	7
-27	-31	97	85	56	49	95	92	-36	-37	155	160	80	65	157	156	33	34	-42	-39
-25	-36	45	34	25	18	40	29	-42	-47	133	135	76	54	140	134				
-22	-32	5	-13	-10	-23	-16	-24	-52	-57	107	111	74	58	117	110				
-46	-55	-35	-60	-53	-68	-64	-75	-59	-66	85	67	69	58	97	84				
-49	-59	-37	-67	-74	-77	-75	-80	-67	-74	66	66	56	50	71	64				
-44	-46	-50	-65	-77	-82	-76	-77	-76	-82	45	45	43	33	53	40				
-44	-45	-48	-54	-75	-87	-72	-72	-87	-90	23	25	29	17	32	20				
-50	-50	-39	-60	-75	-93	-66	-67	-96	-100	1	3	12	-2	9	-6				
-60	-62	-36	-61	-77	-104	-63	-62	-109	-117	-21	-79	-10	-33	-12	-36				
-72	-68	-35	-51	-84	-102	-60	-59	-123	-120	-48	-49	-46	-69	-37	-56				
-81	-73	-47	-65	-86	-90	-56	-51	-134	-124	-65	-69	-75	-86	-69	-72				
-69	-79	-69	-79	-75	-78	-47	-49	-139	-133	-75	-77	-80	-78	-58	-68				
-83	-78	-79	-87	-73	-75	-48	-50	-139	-134	-61	-67	-74	-77	-52	-69				
-90	-89	-85	-88	-74	-74	-54	-55	-134	-134	-48	-58	-83	-80	-52	-73				
								-130	-131	-46	-58	-86	-84	-51	-58				
								-126	-133	-48	-67	-88	-88	-56	-63				
								-122	-130	-55	-68	-88	-89	-63	-66				
								-121	-131	-56	-60	-89	-89	-67	-68				
								-115	-119	-57	-58	-89	-88	-70	-70				
								-118	-117	-66	-66	-90	-88	-72	-69				
								-117	-118	-62	-62	-82	-85	-66	-67				

February 27, 1992									mV Test Pipe Designation									
	1		2		3		4		5		6		7		8		9	
ft*	in	out	in	out	in	out	in	out	in	out	in	out	in	out	in	out	in	out
0	191	190	157	155	147	139	123	119	144	140	128	115	72	92	168	164	171	168
1	193	193	154	163	142	136	115	113	134	132	120	115	74	92	165	163	164	163
2	194	196	149	151	134	131	109	109	126	123	117	112	77	96	165	162	157	156
3	195	197	148	148	130	126	103	102	118	115	111	107	79	97	162	157	150	148
4	188	191	145	144	125	120	95	96	110	105	101	100	79	95	155	149	142	138
5	173	176	140	139	120	114	92	89	99	94	91	90	77	91	144	138	134	128
6	145	147	132	131	114	108	85	81	83	79	75	75	72	85	125	119	124	117
7	105	108	117	116	106	100	81	73	66	61	59	59	66	75	102	95	112	105
8	53	56	91	88	91	85	54	48	46	44	37	37	53	61	77	66	98	88
9	-24	-17	40	34	62	54	40	10	18	22	8	6	20	27	38	24	71	59
10	-109	-100	-22	-29	6	-4	-22	-40	-17	-10	-33	-36	-33	-28	-14	-37	8	-14
11	-177	-164	-72	-87	-62	-82	-41	-101	-56	-54	-80	-85	-88	-89	-83	-102	-63	-91
12	-184	-170	-94	-102	-83	-96	-78	-91	-76	-69	-76	-84	-98	-104	-104	-112	-83	-93
13	-181	-166	-100	-105	-83	-99	-79	-101	-88	-78	-70	-82	-100	-109	-94	-111	-90	-96
14	-178	-173	-103	-105	-85	-95	-85	-98	-87	-78	-65	-81	-113	-118	-90	-110	-92	-101
15	-177	-170	-95	-108	-84	-88	-90	-94	-95	-87	-58	-78	-106	-110	-92	-109	-95	-106
16	-179	-178	-107	-113	-86	-87	-85	-90	-118	-116	-49	-76	-103	-106	-96	-108	-98	-102
17	-180	-177	-114	-122	-89	-86	-80	-87	-95	-100	-46	-73	-101	-102	-102	-103	-101	-106
18	-171	-164	-130	-137	-94	-89	-78	-83	-87	-97	-53	-85	-100	-107	-99	-100	-106	-101
19	-160	-139	-148	-148	-97	-88	-70	-73	-74	-85	-62	-90	-119	-119	-96	-86	-106	-98
20	-142	-142			-95	-96	-75	-75	-79	-79	-83	-83	-127	-132	-96	-79	-100	-99
21															-73	-73		
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February 27, 1992																			
mV Test Pipe Designation																			
10		11		12		13		14		15		16		17		18		19	
in	out	in	out	in	out	in	out	in	out	in	out	in	out	in	out	in	out	in	out
106	92	217	212	155	147	156	143	124	124	232	226	189	164	223	192	231	224	164	156
104	100	221	216	149	134	150	142	121	122	230	232	190	168	214	190	230	225	149	152
111	104	222	217	145	131	150	139	119	120	236	234	190	170	209	186	222	220	136	139
108	106	224	218	141	127	147	135	117	117	237	233	189	171	202	180	213	209	118	122
107	101	220	217	139	121	143	129	114	115	236	232	182	165	196	173	197	195	98	102
99	93	218	214	133	117	137	122	111	111	232	233	172	152	188	164	179	178	75	80
84	76	210	203	124	108	128	113	105	106	225	229	161	138	179	155	157	156	50	56
68	57	196	188	112	99	118	102	98	99	216	221	149	126	167	142	132	135	20	28
48	32	173	164	101	87	107	90	87	88	204	210	137	111	152	128	101	104	-13	-11
15	1	133	123	78	62	90	71	67	67	185	190	117	90	129	102	47	47	-60	-57
-15	-31	85	72	36	11	59	36	40	38	157	160	94	59	104	81	-27	-27	-119	-119
-19	-38	43	20	16	-9	17	-14	29	21	137	137	94	64	92	64				
-21	-30	-6	-36	-14	-47	-28	-66	21	11	113	113	91	69	82	45				
-51	-58	-49	-89	-54	-102	-67	-117	16	7	94	91	84	68	71	28				
-54	-59	-73	-104	-79	-84	-85	-81	10	3	75	69	69	56	58	12				
-54	-61	-70	-109	-84	-90	-89	-83	3	1	51	53	55	40	36	-5				
-56	-60	-72	-107	-82	-103	-88	-81	1	-9	32	33	39	21	21	-26				
-67	-74	-60	-104	-84	-110	-83	-81	-3	-14	12	11	17	-3	0	-44				
-84	-94	-55	-90	-87	-119	-82	-79	-8	-17	-8	-13	-8	-31	-14	-62				
-97	-102	-45	-76	-89	-106	-81	-67	-32	-35	-31	-37	-42	-71	-39	-96				
-110	-112	-57	-80	-90	-88	-64	-64	-60	-65	-46	-53	-70	-84	-51	-115				
-119	-117	-63	-88	-79	-81	-95	-66	-63	-74	-60	-54	-82	-79	-52	-82				
-114	-114	-59	-59	-75	-75	-65	-65	-67	-79	-29	-45	-88	-78	-43	-81				
								-72	-85	-28	-49	-94	-80	-56	-83				
								-77	-87	-37	-60	-95	-85	-60	-74				
								-75	-90	-51	-72	-96	-88	-60	-78				
								-85	-96	-55	-70	-102	-97	-66	-84				
								-78	-95	-55	-70	-106	-100	-69	-78				
								-70	-85	-58	-68	-101	-99	-83	-85				
								-74	-83	-70	-71	-94	-97	-66	-79				
								-53	-53	-18	-18	-36	-36	-28	-28				

APPENDIX A
OBSERVATIONS AND MEASUREMENTS OF PIPE AFTER 6 MONTHS EXPOSURE

General Comments

Corrosion of coupled copper-nickel pipe sections and the copper-nickel separators occurred to a significant degree only on the inlet end which was closest to the alloy 625. Corrosion also occurred on the outside of the pipe under the coupling devices. The magnitude of the corrosion on the outside of the pipe was similar to that on the inside. Frequently, exterior corrosion was concentrated under the rubber seals of the coupling, giving a crevice corrosion-like effect. No corrosion was observed on any alloy 625 pipe, except for a 10-ft separator discussed below. Corrosion of RISICs occurred only on the outlet side, which was made of copper-nickel.

Leg 1—directly coupled—less than 0.1 ft/s

Moderate corrosion occurred on the flange face inner mating ring. Green corrosion product extended about 3 ft down the pipe from the joint.

Leg 2—directly coupled—6 ft/s

Moderate corrosion occurred around the inside of the flange. Shallow, broad areas of corrosion were observed just inside the protruding flange pipe piece. Green corrosion product was seen around the flange end. Broad shallow areas of corrosion occurred within 2 in. "downstream" of the flange weld.

Leg 3—Aeroquip RISIC and coupled—6 ft/s

No corrosion occurred on the flange, but some corrosion was found on the weld. Shallow corrosion occurred just "downstream" of the weld.

RISIC: Very slight corrosion was observed around the inner lip.

Leg 4—Murdock RISIC and coupled—6 ft/s

Significant corrosion observed around weld.

RISIC: Significant corrosion occurred adjacent to the rubber insert. Slight corrosion observed on the face of the flange in the O-ring area.

Leg 5—Aeroquip RISIC and coupled—less than 0.1 ft/s

Some corrosion occurred at the edge of the opening to the interior part of the flange face. Broad, shallow craters were seen in the first 2.5 in. of the flange, estimated to be 2 to 3 mils deep. Scattered shallow craters up to 5 in. were observed "downstream" of the flange.

RISIC: Significant corrosion occurred in the O-ring groove area near the flange. Several craters were estimated at 2 to 5 mils deep.

Leg 6—1-ft Cu/Ni separator—less than 0.1 ft/s

Slight pits were observed within first 2 in., and some corrosion up to 8 in. "downstream."

Separator: No significant corrosion seen.

Leg 7—1-ft alloy 625 separator—less than 0.1 ft/s

The pipe end had significant corrosion. Loss of wall thickness was 21 mils, and craters up to 31 mils deep were visible within the first 2 in.

Leg 8—1-ft Cu/Ni separator—6 ft/s

Considerable corrosion occurred on the pipe end, and some wall thinning was observed. Maximum wall thickness loss was 15 mils. Corrosion was also observed on the outside of the pipe under the coupling. Shallow craters were seen within the first inch.

Separator: Corrosion and shallow cratering was observed, with wall thinning of about 3 mils.

Leg 9—1-ft alloy 625 separator—6 ft/s

Considerable corrosion occurred on the pipe end. Some wall thinning was observed. Maximum wall thickness loss was 16 mils. The deepest corrosion occurred within the first 1.5 in. Some corrosion was observed on the outside under the coupling. Light corrosion occurred in the first 24 in.

Leg 10—3-ft Cu/Ni separator—less than 0.1 ft/s

Fairly deep craters were observed within the first 24 in. in a single line. Shallow craters were just inside the pipe opening. Some corrosion was observed on the pipe exterior under the coupling.

Separator: Corrosion and shallow cratering were observed within the first 12 in., with wall thinning of 7 to 25 mils. Corrosion was observed on the pipe end and on the outside of the pipe under the coupling.

Leg 11—3-ft alloy 625 separator—less than 0.1 ft/s

Shallow craters were observed within the first 24 in. in a single line. Very shallow craters and pits were observed within the first 3 in. Slight corrosion of pipe end was visible. Light to moderate corrosion occurred on the outside of the pipe under the coupling.

Leg 12—3-ft Cu/Ni separator—6 ft/s

Slight corrosion was visible. Two small pits about 1 to 2 mils deep occurred within the first 0.2 in. Slight corrosion was seen of the pipe end. Moderately deep corrosion occurred on the outside under the coupling.

Separator: Light corrosion was observed within the first 1.5 in. Corrosion was observed on the pipe end and on the outside of the pipe under the coupling.

Leg 13—3-ft alloy 625 separator—6 ft/s

No corrosion occurred on the inside of the pipe. Very light corrosion occurred on the outside under the coupling.

Leg 14—10-ft Cu/Ni separator—less than 0.1 ft/s

Light corrosion and minor cratering occurred within the first 18 in. Minor corrosion was seen on the outside under the coupling.

Separator: Minor corrosion occurred within the first 24 in. Very mild corrosion was visible on the outside under the coupling.

Leg 15—10-ft alloy 625 separator—less than 0.1 ft/s

Deep cratering was observed within the first 5 in, with additional corrosion extending 36 in. "downstream." One large crater seen within the first inch was 30 mils deep. Some corrosion occurred on the outside of the pipe under the coupling.

Separator: The alloy 625 separator had severe crevice corrosion on the outside under coupling rubber seal ring. The corrosion was about 0.25 in. wide, 65 to 75 mils deep, and extended at least halfway around the pipe.

Leg 16—10-ft Cu/Ni separator—6 ft/s

Minor corrosion was observed. Light corrosion occurred on the outside of the pipe under the coupling.

Separator: Fairly shallow corrosion and cratering occurred at least 24 in. "downstream." Light corrosion was seen on the end of the pipe. Minor corrosion occurred on the outside under the coupling.

Leg 17—10-ft alloy 625 separator—6 ft/s

Light corrosion was observed. Very light corrosion occurred on the outside under the coupling.

Leg 18—1.5-in. Cu/Ni pipe directly coupled—6 ft/s

Significant corrosion and cratering occurred on the reducer. Small, shallow craters were visible within 1.5 in. in the reduced pipe section. Corrosion on the outside under the coupling resulted in a ring of corrosion about 25 mils deep and 0.25 to 0.5 in. wide.

Leg 19—1-in. Cu/Ni pipe—directly coupled—6 ft/s

Significant corrosion of reducer was evident. Little visible corrosion occurred in the reduced pipe section. Corrosion on the outside under the coupling resulted in a ring of corrosion about 30 mils deep.

APPENDIX B
OBSERVATIONS AND MEASUREMENTS OF PIPE AFTER 1 YEAR EXPOSURE

General Comments

Corrosion of coupled copper-nickel pipe sections and the copper-nickel separators occurred to a significant degree only on the inlet end which was closest to the alloy 625. Corrosion also occurred on the outside of the pipe under the coupling devices. The magnitude of the corrosion on the outside of the pipe was similar to that on the inside. Frequently, exterior corrosion was concentrated under the rubber seals of the coupling, giving a crevice corrosion-like effect. No corrosion was observed on any alloy 625 pipe, except for 10-ft separators discussed below. Corrosion of RISICs occurred only on the outlet side, which was made of copper-nickel.

Leg 1—directly coupled—less than 0.1 ft/s

Moderately deep craters occurred just inside of the flange walls, and heavy corrosion was seen on the lip of the flange. Corrosion extended 7 in. down the pipe, with no significant wall loss beyond that point.

Leg 2—directly coupled—6 ft/s

Heavy corrosion occurred around the inside of the flange. Shallow, broad areas of corrosion were seen just inside the protruding flange pipe piece. Corrosion extended at least 5 in. into the pipe.

Leg 3—Aeroquip RISIC and coupled—6 ft/s

Shallow to moderately deep craters extended about 8 in. into the pipe.

RISIC: A large crater was observed 1.25 in. from the flange face. Minor corrosion was observed at random areas.

Leg 4—Murdock RISIC and coupled—6 ft/s

Moderate corrosion occurred on the flange face. Very shallow craters occurred in the flange interior.

RISIC: Moderate corrosion was seen adjacent to the rubber insert. Shallow, broad craters were observed.

Leg 5—Aeroquip RISIC and coupled—less than 0.1 ft/s

Numerous, moderately deep craters were visible in the flange. Scattered shallow craters were observed up to 12 in. "downstream" of the flange.

RISIC: Deep, heavy corrosion occurred circumferentially about 0.25 in. inward from the flange.

Leg 6—1-ft Cu/Ni separator—less than 0.1 ft/s

A row of distinct craters was observed within the first 9 in., and some corrosion/cratering occurred up to 12 in. "downstream." Light to moderate corrosion was seen on the outside under the coupling.

Separator: Light corrosion occurred inside and outside under the coupling.

Leg 7—1 ft alloy 625 separator—less than 0.1 ft/s

The pipe end had significant corrosion. Extensive corrosion and cratering occurred within at least the first 12 in.

Leg 8—1-ft Cu/Ni separator—6 ft/s

Considerable shallow cratering was observed up to 8 in. into the pipe. Extensive corrosion was observed on the pipe end. Fairly aggressive corrosion was also observed on the outside of the pipe under the coupling.

Separator: No visible internal corrosion was observed. Little corrosion occurred on the outside of the pipe under the coupling.

Leg 9—1-ft alloy 625 separator—6 ft/s

Deep cratering occurred near the end of the pipe. Moderate cratering was observed further "downstream." Shallow craters were seen up to 6 in. into the pipe. Considerable corrosion was seen on the pipe end. Fairly extensive corrosion was also observed on the outside of the pipe under the coupling.

Leg 10—3-ft Cu/Ni separator—less than 0.1 ft/s

A line of prominent craters was observed within the first 8 in. Fairly deep corrosion was seen on the pipe end. Moderate to light corrosion was observed on the pipe exterior under the coupling.

Separator: Moderate cratering was observed within the first 18 in. Light to moderate corrosion was observed on the pipe end and on the outside of the pipe under the coupling.

Leg 11—3-ft alloy 625 separator—less than 0.1 ft/s

Shallow craters were observed within the first 24 in. Light to moderate corrosion on the outside of the pipe occurred under the coupling.

Leg 12—3-ft Cu/Ni separator—6 ft/s

Moderate corrosion was observed on the pipe interior and the pipe end. Moderate corrosion occurred on the outside of the pipe under the coupling.

Separator: Some corrosion was observed within the first inch. Corrosion was observed on the pipe end. Mild to moderate corrosion was observed on the outside of the pipe under the coupling.

Leg 13—3-ft alloy 625 separator—6 ft/s

Slight corrosion occurred on the inside of the pipe. Mild to moderate corrosion was seen on the pipe end and outside under the coupling.

Leg 14—10-ft Cu/Ni separator—less than 0.1 ft/s

Light cratering was observed within at least the first 18 in., and very light corrosion on the pipe end. Minor corrosion occurred on the outside under the coupling.

Separator: Numerous scattered narrow craters were observed on the inside of the pipe for at least 18 in. Light corrosion occurred on the pipe end. Moderate corrosion was seen on the outside under the coupling.

Leg 15—10-ft alloy 625 separator—less than 0.1 ft/s

Light to moderate cratering was observed within at least the first 18 in., with scattered additional deeper craters. Little corrosion occurred on the pipe end. Some corrosion occurred on the outside under the coupling.

Separator: The alloy 625 separator had extensive crevice corrosion on the outside under the coupling at the rubber seal ring. The corrosion was about 1 in. wide, 59 to 90 mils deep, and extended completely around the pipe.

Leg 16—10-ft Cu/Ni separator—6 ft/s

Light cratering was observed only near the pipe end. Light corrosion on the outside of the pipe occurred under the coupling.

Separator: Light corrosion and shallow cratering could be seen at least 36 in. "downstream." Significant corrosion was observed on the end of the pipe. Some corrosion was seen on the outside under the coupling.

Leg 17—10-ft alloy 625 separator—6 ft/s

Light to moderate corrosion was observed in the first 18 in. Moderate corrosion was observed on the pipe end. Moderate corrosion occurred on the outside under the coupling.

Separator: The alloy 625 separator had extensive crevice corrosion on the outside under the coupling rubber seal ring. The corrosion was about 0.5 in. wide, up to 38 mils deep, and extended completely around the pipe.

Leg 18—1.5-in. Cu/Ni pipe directly coupled—6 ft/s

Moderate corrosion was seen just inside of the reducer. The reducer end had lost at least 30 mils in one spot, with moderate corrosion on the remainder of the end. Extensive corrosion occurred on the outside under the coupling.

Leg 19—1-in. Cu/Ni pipe—directly coupled—6 ft/s

Cratering was experienced in the first 1.5 in. of the reducer. Additional cratering was observed "downstream" in the neck of the reducer and into the reduced pipe section. Heavy corrosion was experienced on the end of the reducer. Deep corrosion occurred on the outside under the coupling.

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Because of the difficulty in ensuring full-time electrical isolation of dissimilar metal piping, alternate methods of coping with galvanic corrosion must be used. Use of short, electrically isolated piping sections between dissimilar metals can reduce galvanic corrosion by increasing the electrical resistance of the seawater path through which the galvanic current must flow. The objective of this project was to determine the magnitude and distribution of galvanic corrosion of 70/30 copper-nickel piping when coupled to alloy 625 piping, to determine the efficacy of various lengths of isolated separator pipes made of either alloy, and to determine the amount of stray current corrosion that could occur on the separator piping as a function of pipe material.

The presence of separators of any length in 2-in. pipe lowered the amount of galvanic corrosion between copper-nickel and alloy 625, with a 50- to 60-percent reduction in metal loss using 3-ft (1-m) separators. A further reduction of another 30 to 50 percent was achieved by increasing the separator length to 10 ft (3 m). The use of copper-nickel separators generally resulted in higher metal losses than the use of alloy 625 separators. The effect of the separator was maximum under low flow conditions. Alloy 625 separators were more effective than copper-nickel separators. Smaller diameter copper-nickel pipe experienced higher corrosion rates than pipe of equal diameter to the alloy 625 pipe to which they were coupled. Linearity of potential profile through the separators was an accurate indicator of whether stray current corrosion was taking place.

The Navy should use 3-ft (1-m) titanium separator pipes, electrically isolated at both ends, to minimize galvanic corrosion in 2-in.-diameter dissimilar metal seawater piping joints.

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